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Building Blocks in Space

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This study examines the role of standardization and modularity in solving operational, acquisition, and supportability concerns. The author evaluates the advantages, disadvantages, and difficulties of standardizing military space systems. He examines modular construction as a method of applying standardization to future spacecraft development. Col Marten's conclusiions suggest new alternatives for space vehicle construction during the next decade.

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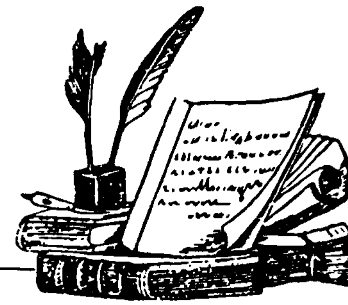

Building Blocks in Space

Martens

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Thank you for your assistance

Research Report No. AU-ARI-89-6

Building Blocks in Space

by

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Contents

ILLUSTRATIONS

Foreword

Air Force space policy establishes three major tenets: Space power will be as decisive in future combat as air power is today; the Air Force must be prepared for the evolution of space power from combat support to the full spectrum of military capabilities; and a solid corporate commitment will be made to integrate space throughout the Air Force. Space system planners of today stand on a threshold of opportunity similar to that of air power planners in the 1920s and 1930s. Effective integration of operational space systems into the military force structure may hold the key to future national security.

Development of space systems is a requirements-intensive process driven by rapidly changing technology and influenced by many organizations. Operational concerns such as flexibility, responsiveness, readiness, survivability, and security are being emphasized by the United States Space Command. Acquisition concerns—such as performance, reliability, modernization, cost, and industrial competition—are being emphasized by the Air Force Systems Command. Supportability concerns such as sustainability and on-orbit servicing are being emphasized by the Air Force Logistics Command. This study examines the role of standardization and modularity in solving these operational, acquisition, and supportability concerns.

Lt Col James D. Martens's research comes at a most opportune time, with the uniqueness of military space systems being critically scrutinized by so many major commands. He evaluates the advantages, disadvantages, and difficulties of standardizing military space systems. He examines modular construction as a method of applying standardization to future spacecraft development. The tremendous value in Colonel Martens's study is the excellent departure point it provides for examining the big-picture impacts, resulting from a shifting emphasis toward operational space systems. His conclusions suggest new alternatives for space vehicle construction during the next decade.

HAROLD W. TODD, Maj Gen, USAF
Commandant
Air War College

About the Author

Lt Col James D. Martens completed this study while assigned to the Airpower Research Institute (ARI), Air University Center for Aerospace Doctrine, Research, and Education (AUCADRE), Maxwell AFB, Alabama. He graduated from the University of North Dakota in 1970 with a bachelor of science degree in mechanical engineering. He was commissioned a second lieutenant in the United States Air Force through the Reserve Officer Training Corps. While in college, he married his high school sweetheart, Karen Lee Hine. His first two years of active duty were spent obtaining a master of science degree in meteorology at Texas A&M University. Following school, Colonel Martens was assigned as a systems analyst with Air Force Global Weather Central at Offutt AFB, Nebraska, where twin sons, Jacob and Joshua, were born. He was then assigned an overseas tour in Panama where he served as staff weather officer to US Southern Command. Returning stateside in 1980, Martens was assigned to the Air Force Weapons Laboratory at Kirtland AFB, New Mexico. As chief of space nuclear power, he was responsible for critical safety analyses involving the launch of radioactive materials on such programs as Galileo, International Solar Polar, and the space shuttle. He was selected to attend the Defense Systems Management College at Fort Belvoir, Virginia, in 1984. Upon graduating, he was assigned to the defense satellite communications system (DSCS) program office, Los Angeles AFS, California. As deputy for engineering, he oversaw integration and testing operations involving the production of DSCS III satellites. Subsequently, he was selected as chief, DSCS Enhancements, where he formulated the acquisition program for the $2-billion DSCS III follow-on program. In 1988 Colonel Martens was selected as Air Force Systems Command research fellow to the Air University Center for Aerospace Doctrine, Research, and Education; he completed Air War College in residence concurrent with this study. Colonel Martens and his family currently reside in Colorado Springs, where he is assigned to Headquarters Air Force Space Command, Peterson AFB, Colorado.

Preface

The complex mission of converting operational requirements into hardware performance specifications is the most challenging yet most gratifying assignment an acquisition manager can have. It was while responsible for the defense satellite communications system phase III follow-on program that I was introduced to the standard spacecraft bus concept.

I am profoundly grateful to Brig Gen Donald C. Walker, then DSCS program manager, for the wisdom and insight to pursue a standard bus for DSCS. The operational flexibility and cost-effectiveness of a common support bus and independent communications payloads had merits that convinced even the "bigger is better" spacecraft builders. The concept offered an attractive method of transitioning the DSCS constellation from super high frequency (SHF) to extremely high frequency (EHF) communications support. When Air Force Systems Command (AFSC) asked for nominations for a research fellow at the Airpower Research Institute (ARI), I applied and suggested research on the role of a standard bus for future spacecraft.

During my first month at ARI, I was privileged to serve on the space launch panel at the first Space Issues Symposium held at Air War College. I was also able to interview several members of the Air Force Blue Ribbon Panel on Space that was being held at Air University during that time. Those two experiences allowed me to focus my research objectives on evaluating the role of modular construction in applying standardization to future spacecraft.

This research has led me to appreciate not only the benefits but also the drawbacks and difficulties in applying standardization to spacecraft development. I hope it will stimulate further research among the operational planners, the system designers, and the acquisition experts who strive to ensure national security through more cost-effective space systems.

James D Martens

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Acknowledgments

My special thanks go to Air Force Systems Command for selecting me as its research fellow and in particular to Maj Gen Thomas C. Brandt for providing the right combination of guidance and freedom to pursue my own approach to the study.

I thank the people at the Airpower Research Institute who contributed much to the successful completion of this project. My advisor, Dr Karl P. Magyar, provided balance to the presentation. My editor, Mr Preston Bryant, played a major role in improving the readability of the document. Lt Col Manfred Koczur provided the pep talks and sanity checks required along the way.

Finally, my deepest appreciation lies with the very special contributions of my family. The bountiful love, editorial advice, and marathon typing by my wife, Karen, got our family through the hectic year. I can never adequately express my love and appreciation for her support. I have a special place in my heart for my sons, Jacob and Joshua, who somehow understood why Dad had to work late hours and weekends. I will always cherish the memories of our special family times in Prattville, Alabama.

Chapter 1

Arrows to Aerospace

During the Middle Ages, the Arsenal of Venice ordered that all bows be made so that standard arrows would fit any of them. This gave the Venetian soldiers an operational advantage over their enemies. During the great industrial revolution of the eighteenth and nineteenth centuries, large factories spread the concept of standardization throughout all facets of industry.[1] Now, through mass production based on standard parts and manufacturing processes, nearly every American family maintains at least one automobile. Similarly, the airline industry operates a network of standardized aircraft and support equipment that has changed the shape of international travel and trade. Standardization of satellites may be the next step.

Standardization can be defined as the adoption of common interchangeable components.[2] Modularity is a design or construction technique that allows standardized modules to be assembled into systems of differing size, complexity, or function. Stereo components and computer peripherals are two examples where modularity has dominated an industry. There are two times to standardize—too early and too late; too early constrains the design, too late increases the cost.[3] The timing for introducing standardization into an industry is crucial. Business theory has identified four stages of development within any industry: the pioneer stage, involving pure innovation and research; a more complex stage that has some broadly defined objectives; an operational stage that introduces routine capabilities; and the commercially viable stage that includes profit making.[4] Standardization was introduced to the manufacture of planes, trains, and automobiles during the operational stage when routine capabilities made it cost-effective.

The operational stage of the space business has arrived. Since the United States Space Command (USSPACECOM) was formed in 1985, increasing emphasis has been placed on the operational responsiveness of military space systems. The operational space shuttle and the proposed space station are making on-orbit spacecraft maintenance and servicing feasible. But tightly constrained budgets are dictating cost-saving trade-offs across both military and civilian space programs.

Air Force Systems Command, Air Force Space Command, and Air Force Logistics Command are expressing high interest in standardizing acquisition, operation, and support of future space systems. The Air Force Blue Ribbon Panel on Space considered standardization a major issue; and at

the first Space Issues Symposium, held at Air University, Maxwell AFB, Alabama, in July 1988, the future space technology panel recommended that standardization and modularity be studied as methods to improve space system operability.[5]

This research examines the efforts made and difficulties encountered in establishing the role of standardization within the developing space business and, in particular, within military space programs. More specifically, it evaluates the application of modular construction to past, present, and future spacecraft.

Chapter 2 discusses the concepts of standardization and modularity and their application within the airline industry. It presents a historical development of the space industry, then discusses standardization and modularity within both Department of Defense (DOD) and civilian space programs.

Chapter 3 addresses the benefits and trade-offs that modularity introduces into spacecraft performance. It introduces four pillars of performance for military systems: force structure, readiness, sustainability, and modernization. It describes each pillar in terms of its application to space systems, and it examines the impacts of modular spacecraft construction on performance.

Chapter 4 focuses on cost. It discusses how standardization and modular construction affect the cost of space systems. It stresses the importance of using life-cycle cost (LCC) in analyzing the cost impacts of standardized systems. It presents an LCC analysis to examine how standardization and modularity trade-offs impact space program costs.

To translate these performance and cost impacts into future spacecraft development, chapter 5 presents current innovations and initiatives within the space industry. It discusses the effects of standardization and modularity on the civilian programs of the National Aeronautics and Space Administration (NASA) and on the military programs of DOD. It presents a brief overview of commercial and international space programs and assesses potential standardization impacts in those areas.

Chapter 6 summarizes the performance and cost impacts of modular construction on space systems and recaps current spacecraft development initiatives within NASA, DOD, commercial, and international programs. It balances standardization factors such as mass production, simplified integration, reduced testing, interoperability, logistical supportability, and modernization in space systems. It draws conclusions on the role of modularity in spacecraft development. Finally, it recommends actions regarding standardization and modularity in the development of future spacecraft.

Notes

1. Col Richard W. Barnes, "Standardization, Competition, and the Weapon System Concept" (thesis, Air War College, Air University, Maxwell AFB, Ala., April 1959), 1.

2. *Glossary: Acquisition Management Acronyms and Terms*, Program Management Course, Defense Systems Management College, Fort Belvoir, Va., December 1983, 66.

3. *Acquisition Strategy Guide*, Defense Systems Management College, Fort Belvoir, Va. (Annapolis, Md.: ARINC Research Corporation, July 1984), 5–57.

4. Sally K. Ride, "Applying the Four Stages of Business Development to Space," *Report on Leadership and America's Future in Space* (Washington, D.C.: National Aeronautics and Space Administration, 1987), 16.

5. At the outset of this research, both the Air Force Blue Ribbon Panel and the first Space Issues Symposium were held at Air University, Maxwell AFB, Ala. These events provided the author a unique opportunity to probe the current status of space issues and concerns. In addition, the author served as a member of the space launch panel at the symposium.

Chapter 2

Highlights in History

The introduction of standardization into industry produced widespread controversy. Although simple in concept and theoretically rich in performance and cost benefits, its realistic application becomes difficult—it may create new problems.

This chapter discusses the concepts of standardization and modularity and reviews their application within the airline industry. Next, it presents a historical development of the space industry. Finally, it discusses the application of standardization and modularity within both DOD and civilian space programs.

Standardization

Standardization is the adoption of common interchangeable components.[1] The concept of a standardization spectrum can be viewed with logistical standardization at one end and functional standardization at the other.[2] However, it must be kept in mind that these are relative and not absolute terms. Logistical standardization means that items are identically manufactured and are identical in operation, maintenance, and logistical requirements. Logistical standardization, then, is the theoretical ideal in which the number of identical interchangeable parts or components is maximized throughout the industry. At the other end of the spectrum, functional standardization means that items are manufactured to be only similar in operation, maintenance, and logistical requirements. In this case, the standardization of each item comes in the way of form, fit, and function (F^3).[3] Functional standardization is a more feasible system; it allows items with the same function to be interchanged without being identical.

Benefits of standardization have been found to result from several different factors. Standard parts permit mass production, which lowers the cost of items produced. The learning experience from producing standard items promotes reliability, thus enhancing operations. Standard items lead to standard procedures, thereby simplifying test and integration requirements. Fewer spare parts and supplies are required to be procured, shipped, stocked, and issued, thereby simplifying the logistic supportability requirements. Standardization allows efficient transfer or interoperability of units, men, and equipment between programs, which reduces training

requirements. Standardization permits economical modernization through the incorporation of new technology with minimal impact on system design.[4]

A review of the aircraft industry shows the benefits since the introduction of F^3 standardization into its mixed fleet. Prior to World War II, transport aircraft were virtually built to custom by a single contractor; there was no standardization of design, construction, or operation. The logistics challenge of operating and maintaining this mixed fleet was nearly insurmountable.[5] Shortly after the war, the Military Air Transport Service (MATS) decided to build three distinct types of transport planes according to size and mission—heavy, medium, or feeder.[6] Each of these types would have standardized parts, operations, and maintenance. Development and production costs decreased, and unit costs were reduced by 30 percent. Aircraft reliability and system lifetime increased. Simplified logistics programs increased supportability. Standard units enabled more procurement source alternatives by breaking out components for production by various contractors. Also, model changes of individual aircraft allowed improved capabilities through new technology insertion.[7]

There are also situations where standardization is difficult to achieve or is undesirable. If only small quantities of an item are required, mass production benefits are unattainable. Interoperability is difficult in technically complex systems, since design solutions lead to many unique items. Incorporation of state-of-the-art technology causes rapid obsolescence and a great diversity between systems developed over a short period of time. Standardization involves performance compromise of certain items, which can impact mission effectiveness. Within the military, limited technical manpower requires dependence on industry for system design; and the resulting economic competition between corporations is a stumbling block to standardization.[8] Before the standardization of the airline industry, there was a lot of apprehension among the designers, manufacturers, and airlines over whether the military would try to enforce such rigid standards that agreement on a national basis would be impossible.[9]

Thirty years ago, one Air Force researcher found "a direct and vital relationship between effectiveness of a military organization and degree to which it possesses standard weapons and equipment."[10] In 1957 the Air Force, realizing both the benefits and the industry apprehension, reviewed standardization within the entire military. The review concluded that lack of standardization was a widespread and costly problem; a great diversity of equipment was used to perform similar or identical functions on various systems.[11]

In attempting to overcome the problems associated with standardization and to maximize the benefits, the military has established a series of specifications that are coordinated with the development status of a system. The specification or "spec" sets the requirements for either certain pieces of equipment or entire systems. Although there are many types of specifications, they can be generally categorized into either design specs or perfor-

mance specs.[12] The two ends of the standardization spectrum, logistical versus functional, may be equated to the design spec versus the performance spec, respectively.

The design spec lays out exactly how an item is to be designed, built, and operated. It produces identical items and is logistically ideal. The performance spec, in its purest sense, merely describes the function an item must perform. During the early development of a new system, when it is still in its conceptual stages, the use of a performance spec allows industry the flexibility of using a diversity of technology to satisfy military requirements, thereby maximizing competition. In fact, commercially available equipment can often be modified to meet military needs at significant cost savings. The design spec, if used too early, would restrict new and emerging technology from the initial design, which could seriously shorten the useful life of the equipment. Once a system moves past the initial development decisions, however, the use of a design spec will lock in the standardization requirements of the selected design. The objective should be to standardize types of equipment to ensure system interoperability and minimize logistical support requirements without impeding technical progress.[13]

Modularity

Modularity is a specialized design or construction process by which a system of standardized units or modules is built.[14] Standardization forces a space system design to meet the most stringent requirements and worst-case environments.[15] Modularity uses the grouping of requirements to develop standard modules that meet performance needs but are independent of system design so as to enable interoperability. The F^3 standards for modules can be categorized as either form/fit or function. Form/fit standards specify shape, size, mass, physical interfaces, and operational environments. The shape, size, and mass define the envelope into which the module must fit to ensure interoperability. Physical interfaces specify electrical, mechanical, and thermal requirements for operation, testing, and servicing. Environmental requirements include such things as contamination, temperature, mechanical stress, and radiation. Functional standards for modules, on the other hand, specify functional interfaces and performance requirements for operation, as well as for testing and servicing. Functional interfaces involve such things as data or mass transfer between modules; performance requirements define the capabilities a module must have to ensure functional interoperability. The key to modularity, then, is the common interface that ensures interoperability of modules. Larger production quantities are possible through standard modules that can be interchanged between systems. Common functional and physical interfaces on standard modules reduce the impacts of technology change in that modules can be upgraded without forcing change on an entire system.[16]

Benefits do result from the common or standard interface. Electrical plugs and gas pump nozzles are two common examples of these standard interfaces. If commercial equipment can satisfy the requirements of any module, only an interface may be needed—and developing only an interface results in considerable savings of both cost and time, as substantiated in military aviation and ground electronics systems.[17] This concept of standard interchangeable modules enables construction of systems differing in size, complexity, or function, thus alleviating many of the concerns brought about by standardization. A common criticism of modular construction has been that reliability penalties result from design compromises to meet interface requirements. However, recent studies on modular designs have shown that reliability is not reduced to a significant degree.[18]

Space Industry Development

Business theory identifies four stages of development within any industry. The pioneer stage involves pure innovation, research, technology, and exploration. The second stage includes the adoption of some broadly defined objectives. Third is the operational stage, in which relatively mature and routine capabilities are introduced. And, finally, the commercially viable fourth stage introduces the potential for profit.[19]

The space business can be traced through these stages beginning with the National Aeronautics and Space Act, signed on 29 July 1958 by President Dwight D. Eisenhower. President Eisenhower established distinctly separate civilian and military space programs. US national space policy involves the interrelationship of the National Aeronautics and Space Administration's (NASA) civilian space program and the Department of Defense's (DOD) military space program. Since space was to be used for only scientific and peaceful purposes, NASA was given the leadership role in the pioneering stage of the space program. The Space Act called for a National Aeronautics and Space Council to provide coordination between NASA and DOD, and to avoid unnecessary duplication of effort, facilities, and equipment. But Eisenhower never appointed an executive secretary and the council never materialized. Rather, he established the Defense Advanced Research Projects Agency (DARPA) to provide coordination and leadership for missile research and space projects by DOD.[20]

Subsequent presidents continued to stress the civilian role in space. President John F. Kennedy's commitment to put a man on the moon by 1969 firmly established NASA as the national space program leader during that decade. However, congressional concern for national security after several Soviet successes in space led to strong support for research in the area of space surveillance technology. Kennedy named the Air Force to be the lead organization for all DOD space research and development (R&D) programs.[21]

As the space business entered into the second developmental stage with different broad objectives for the civilian and military programs, a definite split developed between NASA and DOD. Most DOD programs were conducted in secrecy to deemphasize the military role in space; but the secrecy only increased the coordination problems. During the Johnson, Ford, and Nixon eras, space program funding was severely cut, especially within DOD. President Nixon approved NASA's Skylab and space shuttle programs, however, since these showed potential for commercial and domestic value.[22]

Under President Jimmy Carter, the importance of the space program was reoriented with special emphasis on national security. His policy was aimed at reestablishing the United States' lead in both civilian and military space programs. The interrelationship between NASA and DOD improved. The national security role of space was enhanced to include its use as a war-fighting medium, and antisatellite (ASAT) technology was pursued. In July 1982 President Ronald Reagan announced his national space policy, which emphasized the initiatives started by Carter.[23]

In the 20 years of experience leading up to the mid-1980s, the space business eased itself into its third stage. An array of expendable launch vehicles and the reusable space shuttle made space launch a relatively mature and routine capability. Space technology resulted in a global communications network in which private companies obtained their own satellite television networks.[24] Reagan's policy gradually gave the military more power and influence in national space policy decisions.[25] A space command organization was established within each of the three military services, and a unified United States Space Command (USSPACECOM) emerged to lead all DOD initiatives.[26] The DOD space budget grew steadily; the NASA budget was cut.[27] This led to several problems between NASA and DOD over control of space assets. Duplicate or conflicting programs resulted in budget competition and a reduction in technology sharing.[28] The shuttle accident caused critical shortfalls and expensive reprogramming of several DOD space programs.[29] DOD initiated the National Aerospace Plane (NASP) to ensure that its national security space programs were not totally dependent on NASA's shuttle.[30]

In February 1989 President George Bush formally established the National Space Council. Under the direction of the vice president, this council replaced the DOD/NASA interagency review and coordination processes for space programs.[31] DOD formulated the Defense Space Council to advise the secretary of defense on military space policy and to provide oversight, coordination, and recommendations on all space-related activities.[32]

The space business is entering its fourth stage. American industry is beginning to see a potential for commercial profit in space programs. One company president stated, "We are falling behind the rest of the world and the only way to catch up is to mobilize American industry."[33] The Commercial Space Launch Act of 1984 established the Office of Commercial Space Transportation (OCST) under the Department of Transportation to be the focal point for complex issues affecting commercial interests in space such

as licensing, regulations, safety, and policy development.[34] Some of the largest corporations in America are involved in private space communications satellite programs, and new firms are beginning to develop navigation systems, remote sensing devices, microgravity processing facilities, and space transportation systems.[35]

Modularity in Spacecraft

NASA, believing modularity would one day play a significant role in space system construction, tried to introduce a building-block concept into its early space program. By 1962 NASA engineers had designed a hexagonal space station constructed of six modules, for either habitation or experimentation, attached to a central hub.[36] However, President Kennedy's goal of putting a man on the moon shifted emphasis off the modular space station until after the Apollo lunar landing in 1969. At that time, a presidential task group recommended a four-element space program for the 1970s. It would consist of a space shuttle for launching and servicing satellites, a space tug for maneuvering payloads, a nuclear-powered rocket for transferring satellites to planetary orbits, and a building-block system of modules from which to construct space stations.[37] Only the shuttle portion was approved, however, and that approval was based on the economics of multiple-use, standardized, serviceable satellites. The modular space station, which would serve as a research facility as well as a platform for space operations such as construction, servicing, and launching, was delayed.[38] Since the space station was once again pushed into the future arena, the shuttle era created interest in a standard spacecraft capable of carrying a variety of different payloads.[39]

Within the military, most space projects were thought of as basically research and development programs. Air Force Systems Command (AFSC), the R&D organization for most military space systems, maintained control over these projects throughout their lifetime, from development and test through launch and on-orbit operations.[40] Most space programs placed their heaviest emphasis on developing specialized equipment designed to meet the performance requirements of a specific mission. Standardization was not routinely adopted due to small production quantities, emphasis on incorporating rapidly developing technology, and design constraints caused by size and weight;[41] repair or replacement of equipment in space was technically impossible or unaffordable. Therefore, spacecraft were built with extremely high reliability and redundancy to ensure operation until either the fuel and batteries ran out or they became technically obsolete.[42]

In the mid-1970s NASA began designing a spacecraft with a common bus or framework to which various payloads with a common interface could be attached. The standard or common bus, known as multimission modular spacecraft (MMS), would provide support such as stabilization and pointing, power conditioning, thermal protection, communication, data handling,

orbital maneuvering, and structural support for a wide variety of mission payload modules.[43]

The US Air Force Space Test Program Office became interested in the progress being made by NASA on the standard spacecraft concept. This concept was ideally suited to its unique mission of operationally testing many dissimilar payloads. It sponsored the design of the space test program standard spacecraft (STPSS). Modular in construction, the STPSS was to have the capability of meeting all of its planned payload requirements while realizing the cost savings of a one-time procurement of a fairly large number of spacecraft.[44] By July 1976 the benefits anticipated by early analysis had prompted Secretary of the Air Force John Martin to send NASA a proposed memorandum of agreement (MOA) concerning the procurement of a small multimission modular spacecraft (SMMS) that could be used by NASA, DOD, and other government agencies. The MOA stated that NASA would procure the SMMS with requirements set by both NASA's Goddard Space Flight Center (GSFC) and the Air Force Space Test Program Office. Costs would be shared. The Air Force required an initial operational capability (IOC) to meet a first launch in 1979. In August NASA Associate Director John E. Naugle agreed in principle to the SMMS as a long-term goal but said NASA did not have the budget to meet the early Air Force launch requirements. He proposed that the Air Force use some combination of available hardware to satisfy those missions. This impasse on coordination of budget, schedule, and mission prevented a combined program on modular satellites from developing. The Air Force procured a separate standard spacecraft for its operational test program.[45]

In 1977 the military, anticipating that the combined capability of NASA's shuttle and DOD's planned inertial upper stage (IUS) would lift its large operational payloads, conducted a standardized satellite feasibility and cost-benefit study. Although the study was limited to designing a standard support bus that could carry the mission payload from any one of three existing communication satellites, it led to a belief that the concept could be broadened to other DOD missions.[46] In the study, a spacecraft having separate support and payload modules was designed. The support module provided power, propulsion, telemetry, command, and control. The payload module's standard bays contained the mission equipment. Antennae, panels, and sensors were externally mounted.[47] The study concluded that a standard spacecraft design could be developed for a variety of operational military satellites, and that the design should be modular to avoid gross overdesign and cost inefficiency. Savings in both development cost and production cost would result. Cost savings would increase when the standard bus was developed in conjunction with one of the payload programs, but the anticipated higher reliability would actually be insignificant.[48] Despite the study's encouraging conclusions, however, the standard spacecraft concept was not pursued within the military because of differences in mission requirements and technical phasing between separate operational programs.

NASA, on the other hand, pushed forward with development of the MMS. Its first use was on the solar maximum mission (SMM) launched in 1980. Early fuse problems in the attitude control system (ACS) module resulted in failure for four of the mission's seven scientific experiments. NASA seized the opportunity to plan a repair mission to demonstrate the capabilities of the shuttle and the benefits of modular spacecraft.[49]

The shuttle proved its worth in April 1984 when the SMM was successfully repaired in orbit. This repair mission also demonstrated the interoperability benefits of modular subsystems—the guidance module of the SMM was replaced with one from a different type of spacecraft.[50] Since that time, two commercial communication satellites have been retrieved and returned to orbit by the shuttle, and another satellite was repaired in orbit when it failed to function properly.[51] NASA's MMS, having a common bus with modular payloads, had realized both cost and on-orbit servicing benefits.[52] Programs incorporating that capability today include the earth resources technology satellite (ERTS, known as Landsat), the upper atmospheric research satellite (UARS), and the explorer platform (EP).[53]

The uniqueness of military space systems is now being critically scrutinized due to rapid growth in both size and number of spacecraft and rapid divergence of program costs and DOD budget.[54] Air Force Space Systems Division and the Strategic Defense Initiative Office (SDIO) sponsored a study designed to identify portions of spacecraft where F^3 and interface standards could be applied, thus bringing standardization into the spacecraft industry.[55]

The push toward standardization and modularity is coming from many directions, and the analyses concern many different organizations. USSPACECOM is emphasizing operational concerns for flexibility, responsiveness, readiness, survivability, and security.[56] Air Force Systems Command is emphasizing acquisition concerns such as high performance, reliability, low cost, competition, and the potential for modernization.[57] Air Force Logistics Command is evaluating its role with a growing emphasis on sustainability and on-orbit servicing.[58] Since flexibility quickly diminishes as a program moves into the development stage, Air Force logisticians are calling for a "restructuring of the way we approach design and support of space systems."[59]

Notes

1. *Glossary: Acquisition Management Acronyms and Terms*, Program Management Course, Defense Systems Management College, Fort Belvoir, Va., December 1983, 66.

2. Col Richard W. Barnes, "Standardization, Competition, and the Weapon System Concept" (thesis, Air War College, Air University, Maxwell AFB, Ala., April 1959), 5–7.

3. Ibid., 6.

4. Ibid., 1–2. Col Barnes provides an excellent discussion on the historical benefits of standardization.

5. Maj Gen Laurence S. Kuter, "Standardization of Design and Requirements for Military and Commercial Transport Airplanes" (paper presented to the Society of Automotive

Engineers at the Biltmore Hotel in Los Angeles, Calif., 7 October 1949), 1–3. General Kuter, at that time the commander of the Military Air Transport Service, was attempting to convince industry of the vital need for standardization across the airline industry to support the defense posture of the United States.

6. Ibid., 11.

7. F. Welman et al., *Spacecraft Partitioning and Interface Standardization (SPIS)* (Washington, D.C.: Federal Computer Performance Evaluation and Simulation Center, 1987), iii–v. The history of standardization within the airline industry contained in this document was comprehensive and helpful.

8. This compilation of standardization difficulties was constructed from information presented in Barnes, 107; Kuter, 1–10; Welman et al., 20–25.

9. Kuter, 10.

10. Barnes, 2.

11. Ibid., 11–1_

12. MIL-S-83490, *Specifications, Types, and Forms*, 30 October 1968, 2–3.

13. Barnes, 87.

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Chapter 3

Pillars of Performance

Four pillars of performance have been identified for military systems: force structure, readiness, sustainability, and modernization. Force structure is the number, size, and composition of the units that comprise a system. Readiness is the capability and availability of the system to meet mission requirements. Sustainability is the ability of the system to maintain that readiness throughout the required time. Modernization is the process of upgrading a system.[1] This chapter addresses each of these pillars for space system performance and examines how standardization and modularity may impact that performance.

Force Structure

The space system force structure includes the physical structure of individual spacecraft, the on-orbit constellation required to accomplish the mission, and the infrastructure required for launch and on-orbit operations. Although the primary emphasis of this research is the role of modularity in the design and construction of individual spacecraft, the entire space system force structure will be discussed.

A spacecraft consists of two basic functional units: (1) the payload that directly supports the operational mission; and (2) the bus that includes the structural support, electrical power, data link, attitude control, propulsion, and thermal control subsystems. The bus also provides the interface to the launch vehicle. Spacecraft design is driven by the mission and by the functional requirements of the support subsystems. A recent study has shown that the fundamental mission requirements should be built into a set of functional requirements that can be included in the spacecraft design.[2]

The structural support subsystem is simply the framework for the other subsystems and the payload, and its design is heavily influenced by their size and weight.[3] But its design is also influenced by the integration and support requirements of the launch vehicle. The launch environment—which includes such items as temperature, vibration, acceleration, and contamination—impacts the spacecraft structure. Additional impacts are introduced when payload growth or interchangeable payloads are required.[4]

The electrical power subsystem must supply the energy for all of a spacecraft's equipment. It must meet both peak and average power requirements over the entire design life. The design must be compatible with the data relay system, and it must provide for operation during a solar eclipse. Additional design impacts occur if a growth capability is required.[5]

The data link subsystem handles telemetry, tracking, and command (TT&C) data. Telemetry data is used to monitor spacecraft and payload status and to analyze instrumentation information. Tracking involves beacons or transponders that transmit signals to ground-based tracking stations. Command data is used to execute maneuvers, change spacecraft systems or instrumentation status, and operate experiments.[6] The TT&C subsystem design is driven by payload data rate requirements, signal frequency and distribution, communication security requirements, and data link standards on existing ground control equipment.[7] The three unique ground control systems used for tracking and communicating with satellites are the space to ground link system (SGLS), the spacecraft tracking and data network (STDN), and the tracking and data relay satellite system (TDRSS).[8]

The attitude control subsystem provides for orienting, stabilizing, and maintaining spacecraft attitude within specific limits.[9] Its design is driven by the required stabilization and pointing accuracy. There are two basic types of stabilization: spin and three-axis. Spin stabilization involves a spacecraft rotating about its central axis with the payload mounted on a stationary platform. This allows the payload to maintain a specific pointing attitude toward the earth. Three-axis stabilization involves small internal wheels rotating on three perpendicular axes to maintain spacecraft attitude and pointing.[10]

The propulsion subsystem provides the required fuel and thrust mechanisms. Its design is driven by payload attitude control, orbital insertion, maneuvering, and station-keeping requirements.[11]

The thermal subsystem must ensure that all spacecraft equipment is maintained within its designed operating environment. Both passive and active thermal controls are used to maintain equipment temperatures in the space environment. Passive thermal control involves thermal blankets to retain heat or solar reflectors to reflect heat. Active thermal control involves heaters or radiators. Thermal control design is driven by the placement of equipment and by the type and number of interfaces.[12]

Spacecraft on-orbit constellation requirements are based on their payload mission and operational orbit. Primary spacecraft missions are reconnaissance, early warning, intelligence, surveillance, navigation, communications, weather, and research. Operational spacecraft are found in low earth orbits (LEOs), high altitude orbits, geosynchronous orbits (GEOs), highly elliptical orbits called molniya, and supersynchronous orbits. Each orbit has distinct advantages and disadvantages, and each spacecraft type has a preferred operational orbit in which its mission effectiveness can be optimized.[13]

Space launch infrastructure depends on constellation requirements needed to meet military and civilian operational missions. Launch vehicle design is driven by the physical construction and weight of the spacecraft and the required operational orbit. The national space transportation system (NSTS) serves both civilian and defense users in accordance with national space policy. The Air Force, designated as the DOD executive agent for NSTS to represent national security interests, acts as a partner to NASA in the development, acquisition, and operations of NSTS launch infrastructures. Currently, space launches are handled by either an expendable launch vehicle (ELV) or NASA's shuttle. In the future, two joint Air Force/NASA vehicles, the national aerospace system plane (NASP) and the advanced launch system (ALS), along with a variety of commercial launch vehicles, may be used to satisfy growing requirements. Launch support facilities depend directly on the varieties of launch vehicles and spacecraft they support. Current launch operation centers include Vandenberg AFB, California, and Cape Canaveral AFS, Florida, along with NASA's Kennedy Space Center, Florida.

Separate on-orbit control infrastructures have been established by DOD and NASA. Air Force Space Command operates the Air Force Satellite Control Network, which consists of a satellite control facility and a series of remote tracking stations. It controls DOD spacecraft operations. The Navy has a separate satellite control center at Point Mugu, California, and NASA's Lyndon B. Johnson Space Center, Houston, Texas, controls civilian spacecraft. Operational support infrastructure is dependent on the number of operational spacecraft and the performance of the individual TT&C subsystems.[14]

Spacecraft design involves iterations of compromise between top-down mission requirements and bottom-up engineering principles and processes.[15] The objective of introducing modularity into any spacecraft must be to realize the benefits of standardization without compromising mission accomplishment. A recent DOD study concluded that this objective could be achieved by developing standardized orbital replacement unit (ORU) modules that perform the same basic spacecraft function.[16]

To maximize standardization benefits within the aircraft industry, aircraft were assigned to groups according to size and mission.[17] Similarly, several classes of ORU modules may be developed according to size, orbit, weight, power, and positioning requirements.[18] Functional specifications for the standard ORUs must be developed in sufficient detail to define design specifications for the module interfaces and to clarify hardware/software implementation trade-offs.[19]

Modularity brings flexibility to spacecraft design. It may be introduced at various levels of construction, from boxes to subsystems to the standard spacecraft that uses a common bus as one module. Standard ORU components, boxes, or subsystems can be selectively integrated to meet the unique functional support requirements of the spacecraft; and a standard

spacecraft bus can meet the functional requirements of a variety of interchangeable mission payloads.

In the space test program case study, the objective was to design a standard bus for all military test payloads. Each test payload was first grouped into the type of orbit it required, then matched against potential spacecraft designs. Considerations included weight, orientation, electrical power, data rate, pointing accuracy, thermal requirements, and stability requirements.[20] Performance and cost trade-offs led to selection of the bus that best satisfied the maximum payload requirements.

Such trade-offs had been anticipated by the DOD study that defined a standard bus for military operational spacecraft in 1977. This study, which was limited to a group of three communication spacecraft operating at GEO,[21] concluded that the common bus should have simplified interfaces between bus and payload to minimize expensive integration and launch tasks. The study also concluded that the common bus itself should be modularized to permit adding or substituting standard ORUs.[22] In addition, this study used a standard payload module into which mission equipment could be placed to build unique payloads. For heat distribution, the payloads used a pipe system that was thermally isolated from the bus, thus allowing a payload module to be tested independently from the bus.[23]

The overall impact of modularity on space system force structure is directly related to how spacecraft are grouped. To maximize the cost benefits of modularity, each spacecraft group should include as many types as possible. Larger groups, however, introduce standard modules that have excess capabilities and result in complex interfaces, excess weight, or nonideal form. Space system force structure is very sensitive to such penalties. Complex interfaces decrease reliability, and size and weight increases necessitate performance trade-offs, multiple launches, or increased booster capability.[24]

Readiness

Readiness of space forces is the combination of capability and availability. Capability is established by developing performance specifications to match mission requirements, then designing and building space systems to meet those specifications. A recent Air Force study revealed that the primary performance capability of a spacecraft is not considered by engineers and program managers to be an area of compromise.[25] This is evident in the high performance, highly reliable spacecraft currently in the inventory. For example, the defense satellite communication system phase II (DSCS II) satellites have typically performed twice as long as their design life of five years.[26]

Capability also includes security. Protection of mission data from unauthorized interception is a critical aspect of all DOD space activities. To enhance security, many space systems use cryptologic equipment for

coding and transmitting information. Standardization of this equipment has been maintained by the National Security Agency (NSA). Uniquely designed DOD spacecraft have had to adjust interfaces to match the standardized equipment.

Availability, on the other hand, involves responsiveness and survivability. The commander of the United States Space Command has stressed the need for a more user-responsive space force capable of replenishing losses as they occur and launching quickly in response to unexpected demands. The two leading causes identified for the nonresponsiveness of current systems are: (1) designs that lead to unique spacecraft/booster interfaces and (2) complex prelaunch processing.[27] To overcome these problems, current systems need increased manpower, more launch pads, facility modifications, and alert postures for payloads and boosters. Longer-range initiatives to resolve the problems include spacecraft that have common interfaces to a family of boosters and simplified prelaunch processing.[28]

Modularity emphasizes both the common interface and simplified processing. The standard bus is the simplest example of the common interface. Payload processing at the launch pad varies by spacecraft, but typically involves validation testing of such items as avionics, circuitry, clocks, gyros, antennas, solar cells, structural integrity, and propellant loading. Many systems also perform an end-to-end test of the entire command and telemetry network.[29] This processing normally takes at least one month for DOD payloads.[30] The benefit of modular construction, then, involves the decision to emphasize module-level testing rather than component-level testing to increase responsiveness to failure.[31] The standard module can be replaced quickly to reduce delays in the processing schedule. The key to responsiveness is flexibility, which is gained through the common interface.

The need to ensure survivability of military satellites has been emphasized.[32] Today's space policy specifically declares that "DOD space systems will be designed, developed, and operated to ensure the survivability and endurability of their critical functions at designated levels of conflict."[33] Satellite vulnerability is commonly broken down into three areas: physical damage, false signals induced in the electronics, and jamming of sensors.[34]

Threats of physical damage to US satellites result from ground-based or co-orbital antisatellite (ASAT) weapons that use either projectile interceptors or laser beams.[35] Operational orbit is the main determinant of satellite vulnerability. The greatest vulnerability from interceptor ASATs is to surveillance, weather, and targeting satellites in LEO. The majority of US communications, warning, and navigation satellites in higher orbits are thought to be out of range of ASAT interceptors.[36] Laser ASATs may be either ground or space based. Ground-based lasers could be effective against even hardened satellites in LEO, but pointing and tracking through the atmosphere is a problem. Space-based laser systems would be difficult

or impossible to deploy covertly and could be more expensive than the satellite targeted.[37]

False signals in spacecraft electronics can be induced by either radiation or electromagnetic pulse (EMP) resulting from nuclear explosions above the atmosphere, space-based neutral particle beams, or powerful radar transmitters. Since countermeasures are available for radar and space-based particle beams, high altitude nuclear bursts are the most likely threat to spacecraft electronics. Jamming can be accomplished by radar, infrared, or visible light in the frequency band of a given sensor. Normal countermeasures include frequency hopping, rapid camera lens shuttering, or using frequencies that do not penetrate the atmosphere. These require the enemy to build large, costly, and vulnerable space-based jammers.[38]

Survivability options include hardening the spacecraft against physical or radiation damage, maneuvering, introducing a survivable constellation architecture, or developing an active defense capability.[39] Although satellites cannot be protected against a direct nuclear detonation, hardening against a feasible level of radiation is commonly employed.[40] The lethal range of a one-megaton explosion against a feasible level of hardening is approximately 100 kilometers. The goal of hardening is to require one nuclear burst per satellite, making the attack more complex and expensive.[41] Maneuverability has been introduced on some systems, but it is risky for LEO spacecraft since they are only seen by ground command stations for a limited time and could be lost during the maneuver.[42] Survivable architecture such as proliferation, decoys, and stealth—along with active defense systems such as laser and particle beams—are being studied for use in future space systems.[43] If extensive strategic defenses are deployed on space systems, a complete new dimension of hostile environments will be established and satellites will require enhanced survivability features.[44]

The impact of modularity on survivability trade-offs depends on the mission, its level of priority, and existing backup systems.[45] Hardening of individual modules causes greater weight penalties than those already introduced by modular overdesign. However, selective hardening of modules with mission-sensitive electronics is possible. Maneuvering can be integrated into space systems through a common attack assessment and response module and replaceable fuel tanks, and modularity is adaptable to smaller spacecraft.

Sustainability

Sustainability is the ability to maintain the necessary level and duration of combat activity to achieve national objectives. It depends on providing and maintaining those levels of forces, materials, and consumables necessary to support a military effort.[46] Logistics is the science of planning and carrying out that maintenance.[47] The inaccessibility of operational space

systems has necessitated dependency on high reliability and redundancy rather than maintenance and servicing.

Historically, the logistical support concept has had a primary influence on the standardization and modularity of any system. Studies have identified three unique functions of a logistics support concept for space systems: space assembly, space maintenance, and space servicing.[48] Space assembly is the process where components of a space-based system are deposited in orbit by one or more launch vehicles and then assembled into a complete space unit. This process is commonly accepted as the future method of building large space stations. Space maintenance is the process by which preventive or corrective actions are performed on a space-based system. Space servicing is the process of replenishing fuel and cryogenic material or charging and replacing batteries. Some potential advantages of a space logistics support capability are component repair or replacement, refurbishment of consumables, payload changeout or retrieval, modernization to meet new threat or upgrade technology, and reconstitution of weapons after a test or exercise.[49] Logistical support alternatives include on-orbit servicing, space-based repair, and ground-based repair.[50]

Two factors that limit space system logistics are operational location and spacecraft design. As late as 1983, a space logistics concept study concluded that "the inaccessibility of the operational space segment is the major factor which precludes application of logistics support concepts and utilization of the traditional logistics infrastructure to sustain operations."[51] However, with the ability to service spacecraft in orbit, as demonstrated on the SMM repair mission, the environment for future space logistics is changing. With the capability to access and service on-orbit spacecraft, NASA is calling on potential customers to exploit this new ability by building a viable satellite servicing system.[52]

Military space doctrine now recognizes on-orbit logistics planning and consideration for space maintenance options as essential for satellite design. Air Force regulations state that "an integral responsibility to deploying a Space Force is maintaining it and ensuring that it has enduring capability—thus the Air Force must develop a logistical capability to sustain forces that are based in a space medium. This logistics system should be developed and deployed concurrently with an operational capability."[53]

In developing a viable space logistics system, the designers of new space systems must plan for on-orbit servicing and replacement.[54] Success, therefore, will depend to a large extent on the emphasis given on-orbit servicing and repair in future analyses. Thus, a secretary of the Air Force policy letter states that "the Air Force should actively examine the utility of spacecraft maintenance options . . . and avoid, wherever practicable, design actions which would appear to preclude on-orbit maintenance later in the spacecraft life cycle."[55]

Recent studies by space logisticians have concluded that an on-orbit servicing concept will lead to modular spacecraft with functional require-

ments built into ORUs,[56] depending on spacecraft designs, missions, orbits, and constellations.[57] Space support system logisticians have identified a need to conduct optimum repair level analyses for systems, subsystems, and components.[58]

Supportability through modular ORUs introduces new spacecraft design requirements. Because accessibility is necessary, each ORU should be both thermally self-sufficient and hardened against radiation for on-orbit storage. Built-in test equipment and failure detection equipment will be required for responsiveness, and built-in fault tolerance and redundancy will be needed for reliability and mission effectiveness. Additionally, standardized interfaces for servicing equipment such as tools, fittings, and test equipment will be necessary.[59]

Modernization

Modernization is defined as the technical sophistication of forces, units, weapon systems, and equipment.[60] This definition implies not only the degree to which state-of-the-art technology is included in the original design and construction but, more important, the capability to incorporate upgrades. Historically, spacecraft design has been performance driven and has incorporated state-of-the-art technology. But modernization through significant performance upgrades has generally required complex and costly block changes or complete redesign of the entire system.

Modularity offers the ability to meet new requirements without *replacing* the entire system.[61] The mission effectiveness of specific spacecraft functions could be enhanced by replacement modules that incorporate technology upgrades. Once again, the standard interface is the key. Standard interfaces for functionally similar modules will allow trade-offs by the spacecraft designer, the servicing designer, and the launch system designer while still allowing each to optimize individual systems.[62] Recent studies have shown that well-designed ORUs could allow modernization of an entire space system without replacing the constellation, thereby upgrading system effectiveness while holding down costs.[63]

A factor in determining the benefits of modularizing any particular unit is its susceptibility to reliability growth. If the technology within the unit is likely to be upgraded during the life of the system, modularity will make the modernization more cost-effective.[64] Revolutionary technology breakthroughs, however, are an exception; for example, it is anticipated that the development of miniature spacecraft components under the Space Defense Initiative (SDI) program may do for spacecraft what the chip has done for the computer.[65] Such a technology breakthrough would change the entire space system force structure, including launch control and servicing infrastructure.

Modularity benefits are directly dependent on the relationship of the module's function to the spacecraft mission; for example, modularity

incorporated to enhance the ability to make a spacecraft more maneuverable will be beneficial only if maneuverability increases mission effectiveness.[66] In the case of the common bus, the standard interface will allow payload upgrading without impacting the bus. Standard interfaces also permit module replacement while ensuring that there will be no impact on other spacecraft functions.[67]

Notes

1. JCS Publication 1, *Department of Defense Dictionary of Military and Associated Terms* (Washington, D.C.: Government Printing Office, 1 June 1987), 229.

2. *Autonomous Spacecraft Design and Validation Methodology Handbook, Issue Two* (Kirtland AFB, N.Mex.: Headquarters Air Force Space Technology Center, 31 August 1984), iii–4.

3. *Military Operational Standard Spacecraft Study*, final report (Redondo Beach, Calif.: TRW Defense and Space Systems Group, February 1977), 30–31.

4. Ibid.

5. Ibid., 28–29.

6. Warren G. Heller and Richard LeShack, "Military Geodesy and Geospace Science," *Space-DS614*, (Maxwell AFB, Ala.: Department of Aerospace Doctrine and Strategy, Air War College, April 1988), 1–6. Originally printed in *Unit 4* (Hanscom AFB, Mass.: Air Force Geophysics Laboratory, February 1984).

7. *Military Operational Standard Spacecraft Study*, 28–29.

8. Elwyn D. Haris, *Standard Spacecraft Procurement Analysis: A Case Study in NASA-DOD Coordination in Space Programs*, Rand Report R-2619-RC (Santa Monica, Calif.: Rand Corporation, May 1980), 45.

9. Ibid., 138.

10. *Military Operational Standard Spacecraft Study*, 27.

11. Ibid., 26–27.

12. Ibid., 30–31.

13. Neil Munro, "Military Satellites and Space Programs," *Armed Forces*, March 1987, 123. The advantages, disadvantages, and typical usage of each orbit are outlined by Munro as follows: low earth orbits (LEOs) offer greater resolution of pictures but a shorter satellite life and restricted view; 80 percent of all satellites are in LEO; high-altitude orbits offer longer lifetimes and are used mainly by intelligence, navigation, and research satellites; geosynchronous orbits (GEOs) offer longer life, reduced threat, and continuous earth coverage. GEO is used mainly by communications and reconnaissance satellites; molniya orbits allow better coverage of far northern latitudes but require more satellites to provide continuous coverage. The Soviets use these orbits for navigation, early warning, and communications; the United States uses them primarily for early warning. Supersynchronous orbits offer more protection from attacks and are possible storage sites for reserve satellites.

14. Maj Linas Roe, "DOD Payload Integration in the National Space Transportation System," *Program Manager*, July–August 1987, 2–9.

15. Maj Dalton N. Wirtanen, "Aircraft Subsystem Standardization: A Management Dilemma," research study (Maxwell AFB, Ala.: Air Command and Staff College, May 1977), 23–24.

16. F. Welman et al., *Spacecraft Partitioning and Interface Standardization (SPIS)* (Washington, D.C.: Federal Computer Performance Evaluation and Simulation Center, 1987), 59.

17. Maj Gen Laurence S. Kuter, "Standardization of Design and Requirements for Military and Commercial Transport Airplanes" (paper presented to the Society of Automotive Engineers at the Biltmore Hotel in Los Angeles, Calif., 7 October 1949), 11.

18. Welman et al., 59.

19. *Autonomous Spacecraft Design and Validation Methodology Handbook*, iii–7.

20. Haris, 54.

21. *Military Operational Standard Spacecraft Study*, 2–5.

22. Ibid., 24.

23. Ibid., 163.

24. Welman et al., 23.

25. Maj L. Parker Temple, "Oil and Water," *Air Force Journal of Logistics*, Winter 1986, 5.

26. This example is based on personal experience as deputy for engineering, DSCS Program Office, Headquarters Air Force Space Systems Division, Los Angeles AFS, Calif.

27. This was a fundamental conclusion reached by the National/DOD Space Policy and Doctrine Panel at the Space Issues Symposium held at the Air War College, Maxwell AFB, Ala., on 26–28 July 1988.

28. Ibid., 352.

29. Roe, 38.

30. Ibid., 8.

31. Edward Falkenhayn, "Multimission Modular Spacecraft (MMS) a Serviceable Design Spacecraft," *Proceedings of the 1st European In-Orbit Operations Technology Symposium*, November 1987, 141.

32. Jack Cushman, "AF Starts Satellite Improvement," *Defense Week*, 17 March 1986, 5. The report discussed in this article was issued by the military's Office of Technology Assessment.

33. "Department of Defense Space Policy," *Fact Sheet: Department of Defense Space Policy*, 10 March 1987, 6.

34. Michael M. May, "Safeguarding Our Military Space Systems," *Science*, 18 April 1986, 336.

35. Cushman, 5.

36. Ibid.

37. May, 378.

38. The discussion on false signals and jamming is based on May, 336–37.

39. Ibid., 338–40.

40. James B. Schultz, "Space System Designs Promote Survival of the Fittest," *Defense Electronics*, June 1985, 68–69.

41. May, 337.

42. Schultz, 69.

43. Ibid., 64.

44. May, 340.

45. Ibid., 339.

46. JCS Pub 1, 357.

47. Ibid., 213.

48. Capt David B. Wile, "Space Logistics Technology—The New Challenge," *Air Force Journal of Logistics*, Summer 1988, 31. The identification of these three logistics support functions and their definitions are abstracted from this article.

49. George E. Herring, "Product Support and Maintenance for Space Based Systems," *Logistics Spectrum*, Summer 1988, 39; Maj Neal M. Ely, "A Support Concept for Space-Based SDI Assets," *Air Force Journal of Logistics*, Winter 1988, 18.

50. Herring, 38.

51. Col Roy M. Handsel, *USAF Space Logistics Concept Study—Final Report* (McClellan AFB, Calif.: Sacramento Air Logistics Center, SM-ALC/MMA, 17 June 1983), v–1.

52. Gordon Rysavy, "Customer Concerns Regarding Satellite Servicing" (paper presented at the proceedings of the 1st European In-Orbit Operations Technology Symposium, November 1987), 160–61. Mr Rysavy is the chairman of NASA's Satellite Services System Working Group at Johnson Space Center in Houston, Tex.

53. AFM 1-6, *Military Space Doctrine*, Department of the Air Force, 15 October 1982, 9–12.

54. Temple, 7.

55. Ibid., 5.

56. The Space Logistics Panel at the 1988 Space Issues Symposium concluded that modularity is a critical item in designing future space systems to ensure supportability. This conclusion is also reached by Ely, 20, and Welman et al., 153.

57. Ely, 18.

58. Temple, 7.

59. Herring, 39; Ely, 21.

60. JCS Pub 1, 229.

61. Welman et al., 23.

62. Rysavy, 160.

63. Ely, 18.

64. Welman et al., 21–22.

65. Carolyn Meinel, "Strategic Defense Alliance Spins Off Tiny Technology," *Washington Technology*, 3 August 1988, 1.

66. Ibid., 23.

67. Falkenhayn, 143.

Chapter 4

Realities of Resources

The reality of competing for Department of Defense (DOD) resources leads to a variety of cost reduction efforts. Within space programs, emphasis has been on avoiding high technology designs, using flight-proven components, minimizing demonstration testing, and reducing program office size.[1] This chapter assesses the impact of standardization and modularity on the cost of space programs.

The discussion focuses first on space system acquisition activities and how they are funded within DOD. Standardization theory then leads to a discussion on traditional DOD program manager reaction and the importance of using life-cycle cost (LCC) in analyzing cost impacts of standardized systems. Finally, modular construction is assessed for its cost impacts on space programs throughout DOD.

Space System Acquisition

Funding for military space systems may be broken down into nonrecurring, recurring, and operational support related to the acquisition phase of the system. Nonrecurring costs are the one-time costs associated with designing, developing, manufacturing, integrating, and testing a prototype development model. Recurring costs are associated with fabricating, manufacturing, assembling, integrating, and testing actual flight hardware. Operational costs are associated with spares acquisition, launch, orbit operations, and storage.[2] The relative costs of development, production, and employment of a system will vary depending on the complexity of the spacecraft, the activities involved in each phase, the number of prototype models the constellation required, the operational orbit, and the mission duration.

Development and production costs involve materials and acquisition activities that vary greatly between space systems. For example, some programs build only one prototype unit while others build several. Spacecraft may be procured individually or in blocks of several. Integration and testing activities depend on the complexity of individual subsystems and mission payloads. Production rates may vary from one to several spacecraft per year.[3]

Employment phase costs also vary by space system. The cost for spacecraft spares has been small and generally limited to a few critical

components needed to keep production on schedule. Launch costs, which include launch vehicle, prelaunch processing, integration, and testing, depend on spacecraft weight, size, complexity, and operational orbit.[4] If a space shuttle is used as the launch vehicle, a user fee is paid to the National Aeronautics and Space Administration (NASA).

Spacecraft are sometimes acquired and stored to take advantage of economical production rates; and unplanned events such as the shuttle disaster in 1986 may necessitate additional storage because launch vehicles are not available. Storage costs vary with environmental requirements. Batteries and vacuum tubes, for example, may require atmospheric control. On-orbit storage can be used to reduce costs but it causes deterioration of solar cells, reducing the spacecraft's operational life. Orbit operation costs are associated with spacecraft control and corrections for subsystem failures or attitude changes. These corrections have usually required either switching to redundant subsystems or updating software.[5]

Life-Cycle Cost

Life-cycle cost is the total cost required for development, production, and employment of a system.[6] The difficulty in applying LCC is that the promised long-term cost savings come at a higher up-front cost. This poses several problems for program managers, whose performance is evaluated in terms of staying within fixed budgets. They lack confidence in LCC's projected savings; and no clear criteria have been established for making LCC trade-offs.[7]

Life-cycle cost has received support from several recent studies, however, and is becoming increasingly important. Its use in designing aircraft has been found to produce cost savings after many years of designing only the biggest, the fastest, or the most manueverable;[8] that is, specializing in a particular type of aircraft.

Impacts of Modularity

Modular construction significantly impacts space system cost. Force structure compromises such as complex interfaces, excess weight, and nonideal form cause corresponding cost penalties; but the simplified integration and testing of modular systems lead to cost savings.

Development costs increase by 25 percent and unit production costs increase by 10 percent with modular spacecraft. And the increased weight of modular spacecraft raises launch costs proportionally.[9] Significant cost savings have been projected through the development of a standard bus, however, since the bus normally accounts for 75 percent of a spacecraft's cost.[10] A DOD study conducted in the late 1970s found significant cost savings possible by developing a standard spacecraft bus that could be used

to support three different operational payloads. Development costs for the standard bus were approximately 38 percent lower and production costs were 18 percent lower than those for three independent buses. Payload development and production costs were also reduced—by 2 percent and 4 percent, respectively. This resulted in overall program cost savings of 22 percent for the bus and 3 percent for the payload. Total DOD cost savings for the three programs was 11 percent.[11]

Changing operational requirements and program phasing left many acquisition questions unanswered, however, and the standard spacecraft was not pursued. Nor were the operations and support (O&S) costs for launch and on-orbit operations included in the study. Failure to pursue the potential LCC savings was not unique to this case—an earlier General Accounting Office (GAO) report implied that DOD had not advised the military services of the need to fully explore LCC procurement concepts.[12]

Nevertheless, some studies within the military did find a potential for near-term cost benefits through standardization of modular spacecraft units. One comparison involved the development of 36 standard orbital replacement units (ORUs) that were used across 10 different space programs.[13] The acquisition of standard ORUs would have resulted in lower nonrecurring costs due to fewer development programs, lower recurring costs due to increased production quantities, and lower O&S costs due to fewer types of ORUs. Life-cycle cost savings over a 20-year period were estimated at more than $1 billion.[14]

Logistical support significantly impacts spacecraft cost, and modularity will impact the relative importance of space system O&S costs. The following hypothetical LCC analysis of expendable versus modular supportable spacecraft will help demonstrate this impact. The operational requirement in this example is for a constellation of four spacecraft in GEO with a mission duration of 14 years.[15]

The expendable spacecraft program requires eight spacecraft, each with a seven-year mean mission life, to cover the 14-year duration. This assumes no launch failures. Two development spacecraft are built at a total nonrecurring cost of $800 million. Six production spacecraft are procured at a unit cost of $200 million. O&S costs are $70 million per launch and $10 million per year for on-orbit operations. Storage costs are avoided by delaying production of the last four spacecraft to meet on-orbit need dates. However, a $50-million cost is incurred for production line start-up and minor redesign of components.[16] Total life-cycle cost of the expendable spacecraft program is $2.75 billion.

Using modular construction to provide the capability for on-orbit servicing enables the same operational requirement to be met by only four spacecraft, assuming that servicing doubles their mission life.[17] When cost penalties for modular construction are applied, unit production cost rises to $220 million. The costs for two development spacecraft and two production spacecraft are $1 billion and $440 million respectively, and launch costs rise to $75 million per launch. Total cost for spares is $100 million.

Spacecraft servicing is required every four years after launch, and servicing costs are 10 percent of a spacecraft's unit cost each time it is serviced. Launch costs for repair modules are 30 percent of that required for launching an operational spacecraft. Normal on-orbit operations remain $10 million per year.[18] Total life-cycle cost in this case is $2.52 billion. The life-cycle cost savings due to on-orbit supportability of the modular spacecraft is $230 million.

Similar LCC analyses studying the impact of on-orbit servicing on existing military space programs found only marginal cost benefits. Additionally, these benefits were only found on spacecraft in GEO.[19] These analyses, however, neglected the costs saved through the interoperability of standard spacecraft modules. Development of form, fit, and function standards for ORU modules permits interoperability cost savings between space programs. The extent of the savings is directly dependent on the extent of the interoperability.

Reactions to Standardization

Standardization theory suggests that significant cost savings can be anticipated when standard parts or processes are introduced into an industry. However, the following quote from the assistant for value/cost engineering within DOD illustrates the long-standing frustration in substantiating those savings: "The purist accountant or economist might be disappointed by the lack of completeness, comparability and general paucity of documented work on the dollar benefits of standardization."[20] Perhaps partly because of the "purity of documented . . . benefits," standardization has played a minor role in DOD space systems; cost is often used as a reason.[21]

Contradiction between standardization theory and traditional program actions can be viewed in terms of system trade-offs. For example, a weapon system with a fixed budget may be designed and built without regard to other systems whereas if standardization were employed, that program might have to absorb the additional cost of developing and building overdesigned components or subsystems to meet the requirements of other programs. To a program manager, therefore, standardization may mean a larger and more complex system resulting in increased development, production, and employment costs.[22] The advantages of standardization, then, are mostly associated with a long-term, large-scale view across several weapon systems rather than a short-term, small-scale view of an individual weapon system.

A primary concern in determining the long-term cost benefits of modular spacecraft is the government-civilian cooperation required in the acquisition and use of standard modules. Although Department of Defense acquisition is the largest business enterprise in the world, with annual purchases of nearly $200 billion, DOD makes very little of its own equip-

ment.[23] Instead, it relies on a vast array of industrial companies engaged in substantial commercial development and production.[24] Therefore, the industrial and technological bases of military and civilian spacecraft are complexly intertwined.

If industry is to pursue standard modules, those modules must clearly meet user needs, and a larger marketplace must be ensured. For example, based on projections of DOD, NASA, and the National Oceanographic and Atmospheric Administration (NOAA), a total of 1,479 spacecraft fuel tank modules will be required over the next 20 years. This requirement is obviously larger than for any one program; yet industry is reluctant to pursue standard fuel tank modules until the government supports an on-orbit servicing concept that ensures this market opportunity, and the government is reluctant to ensure the market until satisfactory performance is achieved.[25]

Notes

1. Elwyn D. Haris, *Standard Spacecraft Procurement Analysis: A Case Study in NASA-DOD Coordination in Space Programs*, Rand Report R-2619-RC (Santa Monica, Calif.: Rand Corporation, May 1980), 3.

2. The description of activities involved during each phase of a space system program was adapted from F. Welman et al., *Spacecraft Partitioning and Interface Standardization (SPIS)* (Washington, D.C.: Federal Computer Performance Evaluation and Simulation Center, 1987), 2.

3. Haris, 60, 106–7.

4. Ibid., 62–64.

5. Personal discussions with Aerospace Corporation personnel on the subject of on-orbit storage reveal a general consensus on lower direct storage costs. However, the indirect costs involved in reduced spacecraft life are not well defined.

6. *Glossary, Acquisition Management Acronyms and Terms*, Program Management Course, Defense Systems Management College, Fort Belvoir, Va., December 1983, 39.

7. Lt Col Troy V. Caver, "Life-Cycle Cost: Attitudes and Latitudes," *Defense Management Journal*, July–August 1979, 15.

8. Maj Richard L. Bowman II, "Space—The Logistics Challenge," *Air Force Journal of Logistics*, Spring 1986, 14.

9. Ibid.

10. Henry W. Brandhorst, Jr., Karl A. Fayman, and Robert W. Bercaw, "Spacecraft 2000: The Challenge of the Future," *High Efficiency Space Environment and Array Technology* (Cleveland, Ohio: NASA Louis Research Center, June 1987), 333. The cost of spacecraft by subsystem is: structural and thermal—20 percent, ACS and TT&C—10 percent, propulsion—25 percent, power—20 percent, and payload—25 percent.

11. *Military Operational Standard Spacecraft Study*, final report (Redondo Beach, Calif.: TRW Defense and Space Systems Group, February 1977), 90–91. This study approaches the development cost of a standard bus in two ways. First, the standard bus could be developed by one program but tested over the full range of requirements for all three programs. Second, the standard bus could be developed by one program but independently tested by each program. Payloads were independently developed and tested in each case. Cost estimates for this study were based on experience with tailored satellites and short production lines. Further evaluation of fabrication, integration, and test requirements for larger production quantities was recommended and cost estimates should include options for either the bus or payload contractor to conduct the integration activities.

12. Caver, 13.

13. Welman et al., 53.

14. Ibid., 56. Unit cost estimates for ORUs in this study were based on actual cost data from 10 spacecraft programs within the DOD unmanned spacecraft cost model data base. Cost savings were calculated by first assuming each program developed its own ORUs and then comparing that cost to the case where a standard ORU was developed for several programs.

15. The intention of this example is to emphasize the assumptions required, the relative costs of program phases, and the trade-offs involved. Costs were based on initial estimates for the defense satellite communication system, phase three (DSCS III), follow-on satellite program planned for the mid-1990s.

16. Nonrecurring costs for development models can be estimated by doubling the cost estimate for a unit production spacecraft. This method is regularly used for space system planning purposes. For this example, the unit production cost was $200 million, so each development model was $400 million. Launch costs for the DSCS III follow-on program were estimated to be approximately $70 million per launch based on the use of the planned medium launch vehicle follow-on (MLV-II). On-orbit operation estimates are based on historical expenditures for the DSCS III program.

17. Since operational spacecraft life is normally terminated either by fuel depletion or the failure of a critical component, doubling the spacecraft life by on-orbit servicing is considered a realistic estimate.

18. Bowman, 14. Servicing time is dependent on the reliability and maintainability built into the spacecraft. Actual servicing intervals will depend on individual spacecraft servicing requirements and on-orbit anomalies. Servicing costs vary according to the subsystem being serviced and whether the servicing is done on-orbit, at a space-based facility, or at a ground-based facility. The 30-percent launch cost for ORUs is based on predictions by logisticians of launch costs ranging from 20 to 40 percent, depending on the operational orbit and the location of servicing.

19. R. Chase, *On-Orbit Maintenance Study: Phase One*, final status briefing (Arlington, Va.: ANSER Corporation, August 1988).

20. Dr R. E. Biedenbender, "Standardization Offers Economic Opportunities," *Defense Management Journal*, April 1973, 22–25. Dr Biedenbender was, at the time of this quote, the assistant for value/cost engineering within the Office of the Secretary of Defense (Integration and Logistics).

21. Maj Dalton N. Wirtanen, "Aircraft Subsystem Standardization: A Management Dilemma," research study (Maxwell AFB, Ala.: Air Command and Staff College, May 1977), 26.

22. Maj L. Parker Temple, "Oil and Water," *Air Force Journal of Logistics*, Winter 1986, 5.

23. "A Formula For Action," a report to the president on defense acquisition, President's Blue Ribbon Commission on Defense Management, April 1986, 3.

24. Ibid.

25. Welman et al., 130.

Chapter 5

Innovations and Initiatives

The national space policy commits the United States to maintain preeminence in space. Both the National Aeronautics and Space Administration and the Department of Defense have been tasked to develop pathfinder technologies toward achieving that objective.[1] This chapter discusses space program and technology innovations being pursued by NASA and DOD. Emphasis is placed on the role of modularity and standardization within each initiative. Finally, the increasing roles of commercialization and international cooperation within the national space program are discussed.

National Aeronautics and Space Administration

NASA's multimission modular spacecraft (MMS) was the first major step toward modular construction of space systems. It is a large spacecraft, lower in cost than conventionally built vehicles of comparable size.[2] The MMS was developed as a standard spacecraft bus that could carry the widest possible range of payloads for remote sensing and observation missions. Four reference missions were selected to guide the design specifications. The first three were sun pointing, earth pointing, and stellar pointing from low earth orbit (LEO). The fourth was earth pointing from geosynchronous earth orbit (GEO). Because of its use on the Solar Maximum Mission (SMM), the MMS has been selected for the earth resources technology satellites (ERTS, known also as Landsat), the upper atmospheric research satellite (UARS), and the explorer platform (EP).[3]

The basic MMS design consists of a triangular support structure to which individual subsystem modules and the mission payload adaptor may be attached. It uses standard modules for electrical power, attitude control, and data handling, each of which has several equipment options to accommodate different mission requirements.[4] Individual modules are surface-mounted to facilitate access.[5] A single thermal design, which has no break in the thermal contact at servicing interfaces, is used for all missions.

The design standardizes each module's interface but not the physical or internal configuration of the module. This allows both interoperability of modules between programs and performance upgrades within modules. Antennae, solar arrays, and propulsion subsystems were considered too unique to individual mission requirements to procure as part of the

standard bus. Modular propulsion and solar array subsystems that meet varying requirements are individually integrated to the MMS bus for each mission. The basic MMS with its three integral subsystems weighs approximately 1,400 pounds and can carry a 4,000-pound payload.[6]

The solar maximum repair mission successfully demonstrated spacecraft servicing tasks at all three levels of construction. The entire attitude control subsystem was exchanged, the main electronics box within the power subsystem was replaced, and a plasma baffle was installed to eliminate an unforeseen sensor interference problem.[7] Serviceability has therefore been a key to the operational success of the MMS.

Planners stressed that the serviceable design should not outweigh the overall objective of low cost.[8] The primary cost advantage comes from stressing modular level testing to reduce spacecraft integration and test time. NASA comparisons of integration and test time for MMS satellites versus non-MMS satellites with similar missions verify the savings. Integration and test for Landsat required less than three months, compared to 11 months for its predecessor, the television infrared observation satellite (TIROS); and integration and test for EP required four months, compared to nine months on the geostationary operational environmental satellite (GOES).[9]

Acknowledging the benefits of on-orbit servicing with MMS, NASA has moved into the era of logistically supportable space systems with the Hubble Telescope, the first spacecraft to have designed-in servicing and repair.[10] The 24,000-pound vehicle, built to be launched and repaired by shuttle astronauts, was completed in 1985, but its launch was delayed by the *Challenger* accident.[11] While it is in orbit, batteries and scientific instruments will be replaced every three years and solar arrays every four or five years.[12] NASA plans to continue its serviceable spacecraft line in the 1990s with three observatories to supplement the Hubble Telescope: the Gamma-Ray Observatory, the Advanced X-Ray Astrophysics Facility, and the Space Infrared Telescope Facility. The first will be launched on the shuttle to operate in LEO; the latter two will be launched on expendable launch vehicles (ELVs) to operate in GEO.[13]

NASA has developed a variety of standardized equipment for on-orbit servicing. The three major systems used by the shuttle astronauts are the remote manipulator system (RMS), the extravehicular mobility unit (EMU), and the manual maneuvering unit (MMU).[14] The RMS is used primarily for payload deployment and retrieval, but it may assist in other servicing tasks as required. The EMU is basically a spacesuit that provides environmental protection, life support, and communications for astronauts outside the shuttle. The MMU, a self-supporting backpack that has its own electrical power and propulsion system, provides mobility in space. It has attachments for the modular servicing tool and a variety of other standard servicing tools used to connect and disconnect modules in space.

NASA has also developed standard foot restraint sockets and a series of subminiature connectors for use in repair operations.[15] The flight support

system, a reusable equipment system, provides structural, thermal, and electrical interfaces between various spacecraft and the shuttle. The system includes a docking platform, a test and checkout stand, an orbital replacement unit (ORU) carrier, and a launch and return carrier that fits in the shuttle bay.[16]

NASA's Advanced Programs Office (APO) has stressed that satellites are not only too costly to throw away, they are too numerous to be serviced by the shuttle. To overcome this problem APO has planned a future space system force structure that consists of large platforms, each clustering many payloads and powered by a central utility module. Mission or payload modules will be docked with a manned space station where they will be tested. Once the antennae are deployed, another vehicle will transfer them to their operational orbit where they will be plugged into their host platform.[17]

NASA's long-range goals include exploring Mars and revisiting the Moon.[18] Development of a permanently manned space station is one key to achieving those goals. It will function as a permanent observatory, a communications and data processing link, a transportation node for satellites, a space repair depot, a satellite servicing center, and a launch pad for putting spacecraft into higher orbits.[19] It will be sized and configured to support the mission objectives of assembling and servicing modules, structures, payloads, and equipment in space.[20] The power tower design for the space station, adopted by NASA, has a 450-foot skeletal truss and a set of modular elements that includes housekeeping subsystems, pressurized living quarters, mission payloads, and research facilities. This design allows NASA to use modular construction and yet stay within shuttle launch vehicle constraints.[21] The crew of shuttle mission 61B demonstrated space assembly and construction techniques using a 45-foot truss tower and a large pyramid structure.[22] Space station truss components are scheduled to be ferried into orbit on 19 separate shuttle missions starting as early as 1994.[23] Through NASA's advanced design program, university students around the country are working on various advanced systems for the space station, including the ram-accelerator direct-launch system for transporting cargo.[24]

NASA considers it essential that vehicles and equipment utilizing space station services be multipurpose and have standard interfaces, and designers are currently developing standard servicing equipment such as fuel tankers, rendezvous and docking aids, telerobotic work systems, and multipurpose tools. They are also developing an orbital maneuvering vehicle (OMV) to transport satellites, modules, and servicing equipment between the shuttle and higher operational orbits. Further, an orbital spacecraft consumable resupply system is being designed to transport thousands of pounds of fuel or water for spacecraft servicing by the mid-1990s. It will be capable of supplying either monopropellants or bipropellants to spacecraft from the shuttle, an OMV, or the space station. On-orbit transfer of hydrazine was demonstrated by the orbital resupply

system on shuttle flight 41G in 1984; on-orbit transfer of cryogens will be demonstrated in an experiment called superfluid helium on-orbit transfer in 1991; and a standardized, strap-on attitude control system is being designed for stabilizing disabled satellites and holding them in place during on-orbit servicing operations.[25]

NASA is pursuing robotic servicing and has demonstrated satellite component replacement by robots hundreds of times in ground-based experiments.[26] Long-range plans call for robotic arms to position satellites in docking fixtures where servicing robots perform maintenance and repair,[27] and a flight telerobotic servicer is being developed to maintain space station operations. That latter system will have modular hardware and software to make it capable of on-orbit maintenance and preprogrammed product improvement (P^3I) to support new spacecraft as they become operational.[28]

NASA has been aggressively pursuing standardization and modular construction in particular as cost-effective design techniques that are critical to future on-orbit logistic support plans. Development programs such as the UARS and the EP display a growing reliance on the standard MMS bus. Through longer-range development programs, NASA is building an on-orbit logistical support infrastructure to provide the repairs and services that will be required by its future space systems to maintain preeminence in space. Finally, NASA, industry, academia, and international organizations have jointly published a servicing equipment catalog to aid designers of future space systems.[29]

Department of Defense

DOD's role under the national space policy is to pursue national security objectives. The DOD space program is directed by the USSPACECOM, which has outlined a philosophy of increased operational readiness of its space forces.[30] Toward that end, several new space system concepts—including a standard spacecraft bus, an ORU, a space logistic infrastructure, and a lightweight satellite—have been initiated.

The standard spacecraft bus approach is being pursued by the defense satellite communication system phase three (DSCS III) follow-on program and the space test program (STP). In June 1988 contracts were issued to three separate companies to develop preliminary designs for a standard bus and three communication payload modules. The common bus will carry any of these payload modules, thus allowing DOD to transition from super high frequency (SHF) to extremely high frequency (EHF) communications. A crosslink payload is being developed to increase responsiveness and security by providing spacecraft-to-spacecraft connectivity, thus eliminating groundlink requirements for global communications. DSCS III follow-on satellites will be operational by the late 1990s.[31]

A major goal of the common bus approach is to provide cost-effective and responsive communication support to a variety of DOD and other users.

Operational responsiveness is enhanced by the ability to rapidly integrate the payload needed to fulfill on-orbit requirements. The standard bus reduces cost and increases responsiveness by using common launch and on-orbit control infrastructures for all payloads. And STP has asked contractors for initial design concepts for a space test experiment platform (STEP). STEP will be a standard bus that supports a variety of space test payloads. It is to be constructed with standard subsystems for TT&C, power, and attitude control.[32] Special emphasis is being given to cost-reduction techniques for development and production.

The spacecraft partitioning and interface standardization (SPIS) project has initiated new design and construction techniques focusing on orbital replacement units. To make this concept cost-effective, the designers are stressing interoperability through form, fit, and function (F^3) interface standards. The initial SPIS study looked at spacecraft design practices to define future standardization needs and to select ORUs that show the greatest potential for large cost savings. To simplify standardization terminology, all potentially standard units were classified as ORUs even if they will not actually be replaced on orbit.[33]

That study presented a six-step approach to ORU standardization, the first three of which were accomplished during the study. First, a data base of current spacecraft characteristics and design practices was developed through surveys completed by system program offices, contractors, and professional societies. Second, 37 baseline ORU candidates were selected and evaluated for both architectural independence and wide application across programs (table 1).[34] These baseline candidates, grouped by type, performance, and physical parameters, were then evaluated against future spacecraft missions and nine were identified for near-term standard development.[35]

In step three, the standardization benefits of near-term ORU candidates were evaluated. Future mission projections were used to determine how many ORUs of each type will be required. Benefits were then determined by comparing the cost of using simple baseline ORUs for each program to the cost of using standardized ORUs. In addition, each candidate ORU was evaluated for reliability, acquisition, feasibility, mission effectiveness, and potential for industry acceptance. Six of the standard ORU candidates were found to offer substantial benefits (table 2).[36]

The SPIS study also developed a program to accomplish the final three steps to ORU standardization. First, initial F^3 interface standards, which are being developed for each of the six ORU candidates, are being presented to industry through a series of open forums; and industry comments are being used to finalize F^3 standards for each ORU.[37] Additional steps include the development of a universal format for ORU F^3 standards[38] and a guide for applying standard ORUs to individual spacecraft programs.[39]

TABLE 1

Orbital Replacement Unit Candidates

Spacecraft Subsystem	*Baseline ORU*
Communication and Data Handling	Computer Diplexer Amplifier Transponder Processor Interface Unit Data Storage Device
Structure	Deployment Mechanism Positional Mechanism Separation Devices Launch Mount Ground Handling Lugs
Attitude Control	Computer Sun Sensor Magnetometer Star Tracker Inertial Reference Unit Earth Sensor Drive Electronics Reaction Wheel Magnetic Torquer
Electrical Power	Battery Power Control Unit Power Regulator Signal Conditioner
Thermal	Heater Louvers Radiator Heatpipe Blanket
Propulsion	Orbit Injection Rocket Thruster Iso-valve Propellant Distribution Regulator Heater Fuel Tank

NOTE: Thirty-seven baseline ORU candidates are identified by spacecraft subsystem.

SOURCE: F. Welman et al., *Spacecraft Partitioning and Interface Standardization (SPIS)* (Washington, D.C.: Federal Computer Performance Evaluation and Simulation Center, 1987).

TABLE 2

Standard Orbital Replacement Unit Benefits

Standard ORU	*Benefits*
Battery	High cost savings Allows modernization Wide industry support
Power Control Unit	High cost savings Easy to develop standard Wide industry support
Inertial Reference Unit	Highest cost savings Allows modernization High reliability growth potential
Reaction Wheel	Moderate cost savings High reliability growth potential Favorable industry support
Earth Sensor	High cost savings Easy to develop standard Allows modernization Reliability growth potential
Sun Sensor	Moderate cost savings Easy to develop standard Allows modernization

NOTE: The six standard ORUs that offered the highest near-term potential are shown along with their primary benefits.

SOURCE: F. Welman et al., *Spacecraft Partitioning and Interface Standardization (SPIS)* (Washington, D.C.: Federal Computer Performance Evaluation and Simulation Center, 1987).

The primary purpose of the SPIS study was to introduce the DOD space community to the concept of standard ORUs. An ORU was not considered for standardization if it was assessed that industry would oppose its standardization or if it required civilian and military programs to share resources. Mission payload units were not considered because of their highly specialized nature. Once industry acceptance of ORU standardization is obtained, the program will be expanded to include more complex ORUs.[40] Two significant recommendations came from the SPIS study: a formal DOD program should be established to develop ORU standard interfaces and environmental requirements that support interoperability; and interagency agreements that expand interoperability

throughout DOD, NASA, and the National Oceanic and Atmospheric Administration (NOAA) should be pursued.[41]

Several other spacecraft standardization initiatives within DOD support the modular ORU concept. The satellite on-board attack reporting system (SOARS) program is planning a standard spacecraft module that has the capability to detect attacks against military spacecraft. The Air Force Space Technology Center (AFSTC), Kirtland AFB, New Mexico, is pursuing the standard satellite data-bus initiative. This effort is coordinating microelectronics development around a standard datalink subsystem module. One candidate is the fiber distributed data interface (FDDI). Because of its high data rate capacity, FDDI is being planned for use on DSCS III follow-on as well as on NASA's space station and interplanetary missions. An objective of this program is to develop a standard datalink module for use on both spacecraft and aircraft. AFSTC is also planning the technology for autonomous operational survivability (TAOS) experiments that will attempt to standardize sensors, software, and overall spacecraft architecture.[42]

Initiatives toward the development of a space logistics infrastructure are in support of the Strategic Defense Initiative (SDI) program. Phase one of SDI is a technology-intensive research program designed to assess the potential for building a defense against ballistic missiles.[43] On 4 October 1988 the Defense Acquisition Board approved some SDI technology for full-scale development beginning in late 1989.[44] The space defense system (SDS) baseline architecture includes surveillance and tracking systems for ballistic missiles, kinetic energy weapons, and directed energy weapons.[45] The weapons-basing concept envisions more than 100 small, space-based interceptors mounted on space platforms and grouped into constellations from LEO to GEO.[46] The brilliant pebbles concept maintains a constellation of thousands of small missile defense satellites, each with its own on-board computer.[47]

DOD space policy calls for vigorously pursuing new support concepts at substantially reduced costs while improving responsiveness, capability, reliability, availability, maintainability, and flexibility.[48] Since the SDS will cost billions of dollars, system architects are searching for methods to reduce life-cycle cost.[49] On-orbit servicing and repair has been suggested as the key to cost-effectiveness of space-based strategic defense.[50] The challenge for DOD is to develop a support concept that can accomplish logistics tasks in space, be flexible enough to support diverse architectures, be cost effective, and still be instantaneously responsive to missile attack.[51] On 15 March 1985 Lt Gen James Abrahamson, Space Defense Initiative Office (SDIO) program director, signed an SDI logistics directive that tasked development of an integrated logistics support concept that included on-orbit assembly, maintenance, and repair. It stressed reliability, maintainability, and availability of space forces.[52]

A network of logistics and supportability experts within SDI under an assistant director for logistics integration was established to tie together Air

Force, Army, Navy, OSD, and NASA interests and efforts. The four primary goals outlined by this group were: (1) to establish credible and effective logistics presence within the SDI program; (2) to scope and to define SDI support requirements and options; (3) to assure logistics application for system design; and (4) to advocate space logistics technology development.[53] Logisticians stress that space logistics technology must receive equal priority with sensor and weapon technology if a cost-effective SDS is to be realized. To keep life-cycle cost manageable, on-orbit lifetimes of 10 to 20 years are required. SDIO has developed a logistics infrastructure plan known as the space asset support system. It consists of space-based support platforms for on-orbit storing of ORUs and consumables, vehicles for transferring the ORUs to the spacecraft, fuel or coolant transfer vehicles, and robotic servicers. Besides acting as a supply point, the space-based support platform will be a docking, storage, and secondary maintenance facility for other support equipment.[54]

The SDI supportability research policy lists standardization as its first high-payoff element during conceptual program planning and makes supportability equal with cost, schedule, and performance.[55] Logisticians stress that standardization is essential to reducing the equipment required for servicing and the number of spare ORUs required at the SBSP. SDIO has initiated a program to develop a standard 5–10-kilowatt serviceable power module (SUPER) by 1992. The command, control, and communications (C^3) system for SDS is being designed to have computer processing modules that can be linked together for expanded capability as requirements grow.[56] Interoperability between NASA and DOD force structures is also being stressed. The orbital maneuvering vehicle that is being developed for NASA is under consideration as an SDS transfer vehicle. The OMV performance capabilities are consistent with the SDS support concept, and it is currently being evaluated for potential SDS applications.[57] NASA's contract to build one OMV, scheduled to fly in 1993, has an option for building a second OMV that could be used by DOD to conduct SDS servicing experiments.[58]

Although servicing experiments could start as early as 1993, a servicing infrastructure is not likely until after the year 2000. Planned experiments include robotic servicing, autonomous docking, telerobotic simulation, and complex fluid transfers in space.[59] Key technology areas being studied for robotic servicing include sensing, servicing interfaces, operator interfaces, datalink time delays, and system architecture. A ground-based maintenance control center will be required to operate the SASS. Control center functions will include the planning, scheduling, and monitoring of on-orbit support missions and the distribution of ground-based ORUs, servicing equipment, and spacecraft consumables.[60] The eventual goal is autonomous robotic servicing, but years of research and development with huge program costs are required. Initially, robotic servicers may be controlled from the ground.[61]

The concept of lightweight satellites (lightsats) is being pursued by the Defense Advanced Research Projects Agency (DARPA). Its global low-orbiting message-relay program established the feasibility of military lightsats. The satellite was designed, developed, tested, and launched in less than one year for under $1 million, and it worked successfully for 14 months. DARPA is now planning a $1-billion five-year program to demonstrate lightsat technology and to determine whether operational military commanders need a lightsat capability to augment larger systems.[62]

The multiple satellite system program is investigating the potential use of lightsats for operational DOD programs.[63] These include communications, radar, surveillance, intelligence, navigation, meteorology, and even orbital minefield defense.[64] Lightsat technology is expected to advance state-of-the-art lightweight computer memories, compact UHF antennae, and ephemeris prediction capability.[65]

Lightsats increase survivability of the space system through proliferation. A DOD study estimated that with 350 small satellites, global communications could be maintained even with wartime losses of 75 percent.[66] Lightsats could be launched on the shuttle 20 at a time.[67] DARPA is also investigating the use of Pegasus, a new winged rocket that is launched from an aircraft, as a more cost-effective lightsat launcher. It will launch 10 lightsats simultaneously.[68]

The Navy has shown considerable interest in lightsat development for missions such as transferring messages from sonobouys, collecting and transmitting information for antisubmarine forces, and replacing hydroplane networks that require expensive tending by patrol aircraft.[69] The Naval Postgraduate School is designing a maneuverable 270-pound spacecraft that can accommodate a 100-pound modular payload.[70]

USSPACECOM's philosophy toward operational readiness has emphasized the importance of flexibility, responsiveness, supportability, and survivability. Space system concepts—including the standard bus, interoperable ORUs, a space logistics infrastructure, and lightsats—have been initiated. Modular construction and standardization play a key role in the development of each of these concepts.

Commercial

Private industry has been involved in the US space program since its inception. This involvement has been primarily in the development and production of spacecraft and launch vehicles for the military and for NASA. Purely commercial spacecraft have been developed, although they have had to be launched by NASA. However, a national policy initiative on commercialization of space will result in an era of increased private space ventures.[71] Anticipating the profits to be made in space programs, commercial businesses are rapidly expanding their space efforts. Hughes Aircraft

Company, for example, has designed a three-axis-stabilized standard spacecraft bus (the HS601). The HS601 has modular construction to meet various mission requirements and is intended to compete in markets such as direct broadcast, mobile communications, and imagery.[72] It is also one of the three competitors for DSCS III follow-on standard bus development.[73]

Private industry involvement is expected to produce between 350–400 payloads before the year 2000, promoting expanded efforts in space transportation.[74] At least 20 commercial rocket launches are planned over the next few years by McDonnell Douglas, Martin Marietta, and General Dynamics.[75] Several smaller companies are developing launch vehicles to carry up to 4,000-pound payloads into LEO and up to 600 pounds into geostationary orbit. Estimates of customer launch costs range from $10 to $20 million per launch.[76] Orbital Science Corporation is developing the Pegasus launch vehicle as an inexpensive way to put small payloads into orbit. After air-launching at 40,000 feet, Pegasus reaches orbit in 10 minutes. It can launch a 900-pound payload into LEO but payload size is limited to three feet in length and two feet in diameter.[77] DARPA is supporting Pegasus as a possible lightsat launcher.[78] DOD and NASA are planning to use commercial launch services when feasible.[79] American Rocket Company (AMROC) is finalizing a $1.3 million contract with DOD to launch two experimental SDI payloads on its industrial launch vehicle. NASA is planning to use commercial launch services for its weather satellites.[80] The government is also considering commercial construction of privately owned and operated launch facilities.[81]

Three large commercial space ventures involving on-orbit research facilities are being planned. The industrial space facility (ISF), being developed by Space Industries Incorporated, is a 2,500-cubic-foot, free-flying space platform that can support life when connected to the shuttle.[82] The spacehab module, designed by Spacehab Incorporated, is a pressurized research module that can be flown on the shuttle. Spacehab Incorporated will pay NASA a set fee for each launch and will lease research space.[83] Finally, the shuttle's expendable fuel tanks will be boosted into orbit and made available for research, storage, or manufacturing in space.[84] The University Corporation for Atmospheric Research, involving 57 universities, has submitted a plan to manage the shuttle tanks as laboratories.[85] Scientists feel that if commercial space research facilities are developed, private industry will become much more involved than if they have to compete for use of NASA's space station.[86] Therefore, NASA was directed to arrange funding to support a workable ISF by 1992.[87] The ISF, to be used for research and commercial manufacturing, is to be financed, constructed, and operated by private industry, but the government will lease a majority of the facility.[88] NASA officials are concerned that the $700-million ISF may delay or replace the space station rather than complement it as intended.[89]

International

International involvement in space programs is growing. The United States, Canada, Japan, the USSR, and the European Space Agency (ESA) have active international space programs. NASA's permanently manned space station—being developed by ESA, Japan, Canada, and the United States—is the largest international cooperative space project in history.[90] Formal program agreements, signed on 27 September 1988, call for an operational date in the late 1990s.[91] Japan, Canada, and ESA have already committed $8 billion to the space station program.[92] Japan is building a module for conducting space experiments; Canada is planning to build the mobile servicing system (MSS); and ESA is developing Columbus, the crew module.[93]

ESA is a 13-member cooperative that combines government and industry expertise. It operates several space programs, including a French remote-sensing satellite known as SPOT and the family of French Ariane launch vehicles that provide half of the world's commercial launch activity.[94] US companies are discovering that the administrative costs of launching on the Ariane are much lower that those involved with NASA launches. For example, Martin Marietta found launching their international telecommunications satellite (INTELSAT) cost only a tenth as much on the Ariane.[95]

ESA's latest space programs include: the new Ariane 5 heavy-lift launch vehicle with capabilities similar to the US Saturn V that launched the Apollo lunar mission satellites; the *Columbus* space module that will be a portion of the future US space station; and the Hermes spaceplane, a minishuttle compatible with both the US and Soviet space stations and available for commercial and international users.[96] In addition, a joint US/French satellite, TOPEX/Poseidon, will use radar to map the ocean floor and the currents.[97]

The Soviet space program has traditionally been military oriented, with 90 percent of its 150 operational spacecraft dedicated to either military or joint military-civilian missions.[98] However, more recent Soviet programs have stressed high-technology research and are becoming commercially and internationally oriented. In fact, US companies are marketing Soviet-designed launch vehicles, and the Soviets are carrying international experiments and commercial payloads on their space station.[99] A Soviet program with high commercial payoffs involves development of a spacecraft to utilize solar energy to generate electricity for use on Earth.[100] A four-point bilateral space agreement, signed at the Moscow Summit in May 1988, involves exchanging space data, space hardware, and space scientists as well as conducting independent national studies for future cooperative space missions.[101]

Space program researchers have recommended two large international cooperative programs for the future. The first is an internationally developed and operated family of launch vehicles.[102] The second is a joint

United States/Soviet Union manned flight to Mars. The Mars trip is envisioned as involving large spinning modules to provide artificial gravity for the three-year trip. Soviet space technology, based on extended manned space operations, will lead the module development while the United States will develop a large space-based propulsion system.[103]

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Chapter 6

Recap and Reactions

It has been over 30 years since the world was launched into the space era with the Soviet Union's Sputnik satellite. Today, private industry orbits on the threshold of profit-making space ventures. Just as on the ground and in the air, standardization promises to play a vital role in space. History is very convincing that standardization can provide substantial performance and cost benefits. But history also suggests that standardization can reduce performance and increase costs. How and when standardization is applied will determine the benefit/penalty trade-offs. In general, standardization benefits increase as industry develops and matures.

Summary

Chapter 1 introduced the reader to the purpose of this paper. It discussed the scope of the research and outlined the framework for its presentation.

Chapter 2 provided background information on the historical benefits and problems of standardization. The concept of a standardization spectrum from logistical to functional introduced the importance of standards in form, fit, and function (F^3). Modular construction, which identifies F^3 standards for the interface between modules, was introduced, and a history of modularity within military and civilian space programs was presented.

NASA and DOD have pursued different courses in applying standardization and modularity to their respective space systems. NASA, with its MMS, has emphasized a standard or common bus for a wide variety of payloads and missions. The MMS applies modularity through standard spacecraft subsystems such as power, attitude control, and data handling. These subsystems are then integrated to define a standard spacecraft bus that supports a variety of mission-unique payloads and provides significant performance and cost benefits. NASA is using the MMS on several new spacecraft. The space shuttle program introduced during the 1970s is based on the economics of standardized serviceable satellites. NASA plans outline a future space-based logistics infrastructure.

DOD, bearing the burden of national security concerns, has emphasized the integration of rapidly developing technology. Fighting the launch constraints of payload size and weight, DOD has not concentrated on

standardization or modularity. There are, however, strong indications that the time for change is at hand. USSPACECOM is increasing the emphasis on operational concerns such as flexibility and responsiveness. Austere budgets are causing AF Systems Command to emphasize the need for increased acquisition trade-offs between performance and cost. AF Logistics Command is investigating the potential for spacecraft supportability and on-orbit servicing. Standardization and modularity were identified as potential answers to these concerns by space technology experts at the Space Issues Symposium held at Air University in 1988.

Chapter 3 assessed the benefits and trade-offs of modularity on spacecraft performance. Four pillars of performance for military systems were identified: force structure, readiness, sustainability, and modernization. Each pillar was described in terms of its application to space systems. The impact of modular construction on spacecraft was examined.

Force structure includes the physical spacecraft system and the support infrastructure required to accomplish the mission. The two functional units of a spacecraft are the bus and payload. The bus consists of subsystems for structural support, electrical power, datalink, attitude control, propulsion, and thermal control. Spacecraft design is dependent on the functional capabilities of the subsystems; and subsystem capabilities depend on the performance requirements of the mission payload. Modular construction within a spacecraft ranges from a component, a box, or a subsystem module to an entire bus module that can support a variety of interchangeable payload modules.

Regardless of the level at which modularity exists, only functional standards are needed to define the performance requirements of individual modules; the need to include form and fit to identify F^3 standards is limited to the interface between modules. To achieve the widest possible use of modularity, spacecraft must be grouped in such a way that common functional standards can be defined for each module. A number of studies indicate that spacecraft can best be grouped by some combination of mission and orbit, and that the overall impact of modularity on force structure is directly related to how the spacecraft are grouped. Large groups will result in modules with excess capabilities in one area of performance and shortfalls in other areas; small groups will not achieve the cost benefits of standardization.

Spacecraft modularity also influenced the design of launch and control infrastructures. Standard F^3 interfaces between spacecraft and launch vehicles simplify design and construction of both boosters and launch support systems. Standard F^3 datalink modules simplify design and construction of operational control infrastructures.

Modularity may significantly impact readiness, which is the capability and availability of a spacecraft to meet its mission requirements. Capability refers to the primary mission payload performance. Modular construction must not compromise capability to such a degree that mission requirements

can no longer be met. Within DOD, capability also includes security. Modularity has historically played a significant role in this area through standard cryptographic modules, which are used across a variety of spacecraft.

The second part of readiness is availability, which includes both responsiveness and survivability. Spacecraft that support national security must be launched quickly in response to unexpected demands and must be replenished quickly as losses occur. Modularity adds responsiveness through both simplified prelaunch processing and flexible launch capability. To maintain readiness, operational military spacecraft must be able to survive physical damage, false electronic signals, and sensor jamming.

Survivability options include hardening, maneuvering, changing constellation architecture, and developing active defense systems. Modular construction either complicates or enhances hardening efforts, depending on the specific mission survivability requirements. Hardening individual modules may add to any weight penalties already introduced by modular design. If all the mission-sensitive electronics can be concentrated into one or two hardened modules, however, weight penalties might actually be reduced. Standard buses may be built in hardened or nonhardened versions. Spacecraft maneuvering capability can be added by integrating a standard module for attack assessment and response. Smaller modular spacecraft are more adaptable to proliferation, decoys, and stealth technology that complicate targeting by enemy ASATs and enhance constellation survivability. Modules containing active defense systems can be produced for use with various spacecraft.

Air Force regulations recognize space logistics as vital to future operational capability. The need for logistics planning in the design of future space systems is being widely stressed. Modularity can play a significant role in the sustainability of future spacecraft. Sustainability, the ability to maintain required readiness throughout a system's operational life, is critical to the success of military systems. Modular spacecraft, constructed by integrating ORUs to meet mission functional requirements, enable on-orbit servicing and repair to increase operational life. Logistical repair level analyses of ORUs are necessary for the establishment of standards that define the optimum level of modularity for both spacecraft and space logistics support infrastructure.

Modernization involves both the technical sophistication of a system and its capacity to incorporate upgrades. Modularity offers the flexibility required to upgrade modules, to meet new threats, or to incorporate new technology, without affecting total system design. Modular construction significantly enhances modernization benefits if modular upgrades increase reliability and mission effectiveness. The drawback to F^3 interface standards is that they severely restrict the introduction of revolutionary technology advances.

Chapter 4 presented the benefits and trade-offs of standardization and modularity relative to spacecraft cost. The importance of LCC in evaluating system trade-offs was discussed. A sample LCC analysis examined how standardization and modularity trade-offs may affect space program costs.

Funding for military systems is divided into nonrecurring costs, recurring costs, and operational support costs, each related to a system acquisition phase (development, production, or employment). Standardization has been proven to save costs on many systems, but until recently, DOD acquisition and cost accounting procedures have not emphasized LCC. No clear criteria have been established for spacecraft LCC trade-off analyses. Studies have shown that modular spacecraft construction can produce LCC savings. Like any savings plan, modularity has up-front investment costs. Modular spacecraft usually cost more to develop and produce because small quantities are involved. Development and production costs will be reduced if standard interoperable modules are used across a variety of space programs. Separate studies have revealed LCC savings either through a standard bus with interchangeable mission payloads or a spacecraft constructed of standard ORUs. The standard bus will reduce the number of development programs required and will encourage industry to fund a greater share of costs since it could be marketed for commercial as well as military ventures. Modularity at the ORU level produces cost savings through increased production quantities and expands competition by allowing smaller contractors, who specialize in a specific technology, to compete with larger spacecraft contractors.

Maximizing the long-term cost benefits of modular spacecraft will require a coordinated national space program that includes established standardization objectives and a common space logistics support system to ensure a stable market opportunity. The cost of developing the space logistics infrastructure, required to gain the supportability benefits of modular spacecraft, must be amortized by widespread application across DOD, NASA, and commercial users.

Chapter 5 discussed innovations and initiatives currently taking place in spacecraft standardization and modularity. Both civilian and military programs were presented and a brief overview of commercial and international space programs was given. With the success of its initial missions, NASA is pushing ahead with the MMS. In addition, NASA is designing a new era of logistically supportable spacecraft observatories, including the Hubble Telescope, the Gamma Ray Observatory, the Advanced X-Ray Astrophysics Facility, and the Space Infrared Telescope Facility. NASA has outlined a future space force structure consisting of large platforms, each clustering a variety of payloads. A complex on-orbit space logistics support system includes a permanently manned space station. Modular construction of platforms, payloads, and servicing equipment is being aggressively pursued along with standard interfaces that are critical to a cost-effective logistics support plan.

DOD space policy, emphasizing operational readiness and proliferated systems, asserts the importance of flexibility, sustainability, survivability, and responsiveness. Two major efforts being pursued in design and construction techniques for future military spacecraft are the standard bus and the ORU. They represent two different levels of modularity within space systems. The standard bus approach considers the entire spacecraft bus as a separate module with a standard F^3 interface to the mission payload. Benefits of this concept are based on identifying a group of payloads whose mission and orbital support requirements can be satisfied through the standard interface.

Although Air Force studies on the standard bus concept have shown the potential for large cost savings, individual program concerns have kept it from being adopted. The DSCS program is pursuing a standard bus to provide operational flexibility, launch responsiveness, and significant cost savings for the next generation of spacecraft. The standard bus has particularly good potential for performance and cost benefits at this time since DSCS is transitioning from super high frequency to extremely high frequency for communication support. Each independent payload for SHF, EHF, and a spacecraft-to-spacecraft crosslink will use the standard DSCS bus. A standard bus is also being considered for use as a space test experiment platform.

ORUs have an expanded role in modular construction. F^3 interfaces can be defined at a much lower level of construction, allowing standardization across a wider spectrum of space programs. Various initiatives on new spacecraft design techniques are focusing on the use of ORUs. The spacecraft partitioning and interface standardization (SPIS) project is defining initial ORU candidates and developing F^3 interface standards. Various programs are developing individual modules, with capabilities such as attack reporting and data interfacing, that will serve as design standards. Although industry is participating in the development of ORU standards, no interagency agreements exist to ensure interoperability of modules between government programs.

SDIO has taken major initiatives toward the development of a space logistics infrastructure. The planned space defense system support assets will consist of storage platforms, transfer vehicles, and robotic servicers. A network of Air Force, Army, Navy, OSD, and NASA supportability experts has been established to integrate the space logistics support concept. They have stressed that space logistics technology must receive equal priority with spacecraft design technology and that standardization is essential to achieving a cost-effective system.

Lightsats, being pursued by DARPA, reduce cost through smaller and less-complex spacecraft, increase responsiveness through simplified integration and testing, and increase survivability through proliferation. The operational use of lightsats for communication, radar, surveillance, intelligence, navigation, meteorology, and space weapons is being investigated.

Factors Favoring Standardization and Modularity

Standardization, the adoption of common interchangeable components, achieves its benefits from mass production, simplified integration, reduced testing, interoperability, and logistical supportability. Standard components can be made in larger quantities, permitting low-cost mass production. The increased reliability resulting from standard components enhances performance. Standard components lead to standard procedures that simplify integration and reduce testing requirements. Simplified integration and testing reduces development and production costs, shortens development time, and increases readiness. Standardization results in fewer spares to be procured, shipped, stocked, and issued, thereby simplifying support requirements and lowering logistical supportability costs. Standardization also simplifies maintainability through standard repair equipment and processes. Interoperability of standard components enables efficient transfer of parts, personnel, and equipment between programs.

Modular construction applies standardization through F^3 interface standards. Standard modules, each performing a specific function, may be assembled like building blocks to construct a system that meets unique mission requirements. Interoperability is ensured through standard modules while the flexibility of internal module design is maintained. Interoperability leads to the cost benefits of larger production quantities. Standard interfaces simplify integration, reduce testing, and increase supportability. Modularity provides the additional benefit of modernization. New technology or upgrades in capability can be introduced into a system through a new module if the F^3 interface remains standard. Significant development cost and excessive time are avoided by localizing the redesign to a module.

Factors Opposing Standardization and Modularity

Standardization involves compromise. Either performance penalties or cost penalties will result when a standard component is used in several systems with different support requirements. A standard electric power module, for example, may be used in two systems with different requirements. If it meets the higher-power system requirements, it is a more complex and more expensive unit than needed for the lower-power system. If, on the other hand, it is only designed to meet the lower-power system requirements, higher-power system performance is reduced. Even when standard low-power modules are linked together to meet the higher-power system requirements, complexity and cost are added to the system.

Attempting to apply standardization to the space industry in the same way it is applied to the automobile and aircraft industries reveals several

problems. Unlike automobiles that are produced by the thousands, an operational constellation of satellites generally consists of less than 20; therefore, the benefits of mass production are not achievable. Standardization is not a major concern for a one-time integration of complex technology where every square inch is vital and each pound costs thousands of dollars to launch. Cost benefits of reduced testing may become insignificant when the failure of any subsystem renders a $100-million piece of hardware useless and places national security in jeopardy.

Interoperability is complicated when unique complex systems are required, and cost savings are insignificant when small numbers of spacecraft are involved. Logistical support has not been developed due to the inaccessibility of operational systems in space. Modernization through integrating new technology into existing spacecraft has not been a design concern. Incorporation of rapid technological advances has been achieved through frequent system redesigns that are necessitated by short operational lifetimes and expanding space system requirements.

Balancing the Factors

As the space industry develops and matures, opportunities for performance and cost benefits through standardization increase. Numerous studies since the mid-1970s have revealed the potential benefits through standardization within the space industry. Yet, individual program concerns and short-range budget problems have defeated all attempts to pursue widespread benefits.

NASA has demonstrated both performance and cost benefits through its standard MMS bus. The space test program and the DSCS program are attempting to apply the standard bus concept to military spacecraft. Performance and cost benefits calculated for these programs indicate that the standard bus should be evaluated across a much wider range of operational missions. The standard bus will simplify space force structure by making possible common launch and on-orbit control infrastructures. System readiness will be enhanced by the flexibility and launch responsiveness of an interoperable bus. Sustainability and readiness will be enhanced by the increased reliability and availability provided by larger production quantities. Sustainability will be further augmented by on-orbit payload exchange once a space logistics capability is developed. System modernization will be introduced by the ability to upgrade or develop new communications payloads without affecting production of the standard bus. Localizing the design changes to the payload module while maintaining the standard interface will provide more cost-effective modernization.

The standard spacecraft bus will produce cost benefits from reduced bus development programs and a common launch and on-orbit control infrastructure. Additionally, contractors will compete to develop and produce individual payloads separate from the standard bus, increasing competition

and limiting the range of technological expertise required under each contract. Individual users will play a more significant role in developing the payload since they will not be involved in the complexities of bus development.

The standard bus concept, however, has limits to its applicability. Designing one standard bus to meet too many support requirements causes complexity, size, and weight penalties. Payload performance compromises or higher launch costs, resulting from a standard bus, may be unacceptable or may outweigh the development and production cost savings. And if one company is awarded the total production contract for a standard bus, it could monopolize the spacecraft industry. Acquisition techniques that maintain a competitive industrial base, such as splitting production quantities between two contractors, will be needed. From a national security standpoint, the unwanted transfer of technology to adversaries becomes much more of a problem when more and larger non-DOD programs are involved. Such transfers could seriously compromise military capabilities.

Modularity will expand standardization benefits to lower levels of spacecraft construction by partitioning functional support capabilities and defining standard ORUs for each function. Modular ORUs add the flexibility of selectively standardizing any space system to ensure cost-effectiveness without limiting mission performance. An electrical power subsystem could use a series of battery modules or modular solar panels to increase its electrical power capability. A modular propulsion subsystem could be used to vary the fuel available for orbital injection of lighter or heavier payloads, lengthening a spacecraft's life or adding a maneuvering capability. Integration of functional ORU modules will allow the development of standard buses for different types of payloads. A family of standard buses will then satisfy diverse future space requirements.

Modularity, then, is a promising method of applying standardization to the space industry. To realize maximum performance and cost benefits of modular spacecraft, standardization across DOD, NASA, and commercial programs is essential. Widespread standardization has the additional advantage of allowing DOD to use NASA or commercial spacecraft to augment military forces during wartime, just as they plan to use the reserve fleet of commercial aircraft. Spacecraft standardization through modular construction will be a slow and gradual process with major changes in spacecraft design and system architecture. Significant impacts on existing launch and control infrastructure must be minimized.

Space maintenance and servicing are greatly simplified through modularity and can result in huge cost savings for future space systems. DOD and NASA requirements for a space-servicing infrastructure are similar. Although routine servicing is many years away, both DOD and NASA are developing space-servicing concepts that include storage platforms, orbital transfer vehicles, and repair equipment. Current concepts, however, are being driven primarily by logisticians who have had limited interaction with spacecraft designers. This emphasis on the employment

phase over the development and production phases could restrict spacecraft design and ultimately raise life-cycle costs.

Recommendations

Responsibility for ensuring emphasis on spacecraft standardization efforts must begin with the National Space Council. A coordinated national program is needed to maximize the benefits of standardization and to avoid an unbalanced approach. National space policy, including objectives and goals for standardization, should be established and monitored to ensure a cost-effective national program. These objectives should include a common space logistics support system that will ensure a stable commercial market opportunity.

Within DOD, the Defense Space Council must ensure that standardization initiatives are aggressively pursued. DOD objectives and goals should be coordinated with NASA and commercial programs. The Air Force, as the lead service for space systems, should retain responsibility for coordinating standardization efforts among all military space vehicles and launch systems, including SDI. Integration of AFSPACECOM operational concerns, AFSC acquisition concerns, and AFLC supportability concerns can only be addressed at the Air Force level.

Standardization of DOD spacecraft design should be focused within the independent systems engineering organization of Space Systems Division, Air Force Systems Command. Among its responsibilities should be the establishment of spacecraft F^3 interface standards. Standardization efforts should be pursued with the near-term objectives of increased operational responsiveness and decreased development and production costs. Long-term objectives should include the introduction of logistics supportability to decrease life-cycle cost. To ensure launch responsiveness, interface standards must be established between all planned spacecraft and existing or planned launch vehicles. The interface standard must minimize design impacts on both spacecraft and launch vehicles.

The DSCS standard bus should be evaluated to identify other mission payloads that can also utilize it. A standard spacecraft bus for communications payloads is the logical first step, given the wide variety of communications users throughout DOD, other government agencies, and the private sector. Most communications satellites use the geosynchronous orbit; it is therefore possible to derive a large group of unique payloads with both a common mission of communications and a common orbit. A standard bus that supports each of these payloads can enhance performance capabilities and reduce costs. Early identification of additional payloads will minimize design impacts on both the common bus and the payloads.

The potential for expanding the standard bus concept by developing families of multiuser spacecraft buses should be evaluated. This recom-

mendation involves a complete new way of pursuing spacecraft design by separating the bus from the payload development. In-depth studies of future space requirements are needed to derive specific groupings of operational systems and to determine the optimum application for the standard bus. One or several types of standard buses may be able to support all communications payloads. A variety of mission payloads using LEO—such as weather, surveillance, research, and mapping—may be able to use the same common bus. Wherever the concept is cost-effective, a special system program office (SPO), responsible for bus procurement, payload integration, and launch operations, should be formed. This will allow payload SPOs to concentrate their efforts on operational payload requirements rather than launch and on-orbit support functions. This concept also simplifies the infrastructure and operations for on-orbit control of spacecraft by limiting integration requirements.

Modular construction initiatives should be aggressively pursued throughout the national space program to introduce the operational responsiveness benefits of spacecraft standardization. Efforts to identify standard ORUs and to develop corresponding F^3 specifications should be expanded. Operational responsiveness, technology modernization, and logistical supportability should be emphasized. New developments within the emerging commercial spacecraft and launch vehicle industry should be evaluated for concepts or hardware that can be applied to DOD programs.

The Air Force should continue to study the feasibility of on-orbit servicing. A thorough evaluation of NASA and SDI concepts is needed to establish a coordinated military policy and doctrine on spacecraft servicing. A space logistics strategy must then be established to guide the design and development of both spacecraft and servicing infrastructure.

National policy, objectives, and goals on space system standardization should be established. Cooperative standardization initiatives involving NASA, DOD, and commercial programs must be pursued where possible without jeopardizing uniquely designed research and development spacecraft. Families of multiuser buses, rapid expansion of standard ORU development, advances in spacecraft technology, and establishment of a space-based logistics infrastructure will ensure cost-effective development of modular building blocks in space.

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